Acoustic factors affecting the dynamic range of a choir

Ingo R. Titze^{a)} and Lynn Maxfield

National Center for Voice and Speech, 136 South Main Street, Suite 320, Salt Lake City, Utah 84101-3306, USA

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Based on the assumption that individual sound intensities of singers are incoherent and add linearly to produce a combined choir intensity, a model of a voice range profile of a choir is produced. It is shown that this model predicts six distinct levels of choir dynamics (*pp p mp mf f ff*) over two octaves of fundamental frequency in a choir section. The levels are 3–6 dB apart, depending on the individual voice range profiles of the singers. Overall choir size has no effect on dynamic range, unless the size is varied dynamically by not all singers singing all the time. For a non-homogeneous group of singers, a few loud voices dominate *ff* if everyone sings, while *pp* is not achieved effectively without suppressing all voices that cannot sing soft. Furthermore, the dynamic range can be significantly limited when choral blend for loudness is imposed on a non-homogeneous choir. © 2017 Acoustical Society of America. <https://doi.org/10.1121/1.5004569>

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I. INTRODUCTION

Choirs range in size from less than a dozen singers to more than a thousand. It is undeniable that a large choir can make a louder sound than a small choir, but it is less clear that a large choir generally produce a greater dynamic loudness range than a small choir. Overall loudness, and loudness range, are largely determined by the combined intensity of the singers, although spectral content, vibrato, and various other frequency and amplitude modulations play a role in perceived loudness (Gauffin and Sundberg, 1980, 1989). It is shown here how the intensity range of any choir depends on the intensity range of each individual singer, the degree to which individual intensity ranges are allowed to differ in a choral blend, and the dynamic recruitment of individual singers (rarely used to a full extent). The study is a modest theoretical contribution at this stage, laying the groundwork for future studies with specific ensembles in various performance venues.

A review paper of research conducted on choir acoustics (Ternström, 2003) revealed that the primary emphasis has been on intonation, vibrato, spectral effects, spacing of individuals, and choir blend. Relatively little has been written about specific factors involved in choir dynamics. Coleman (1994) reported dynamic ranges of individual choir singers to range from 11 to 33 dB. A main difference between well-trained singers and less trained singers was the ability of trained singers to produce softer sounds.

Rossing *et al.* (1986) compared voice use in solo versus choral singing by recording a group of singers performing in both choral and solo “mode.” Using a long-term-average spectrum (LTAS), they determined that in solo mode, the singers tended to produce more energy in the singer’s formant region of the spectrum. Inversely, the LTAS of the singers’ samples during choral singing exhibited higher

energy in the fundamental frequency region. Perhaps more pertinent to the current discussion was their finding that the singers tended to match their voice levels to the singers around them. No such level matching was observed between the singer and the accompaniment during the solo singing samples. The authors noted that this observation was far from unexpected. However, the implication of choir singers trying to match the level of their neighbor would appear to influence the overall dynamic levels of the choir, as will be shown here. A later analysis of LTAS of boy, youth, and adult choirs in different rooms (Ternström, 1993) indicated that the boy choir was capable of producing an overall dynamic range of 12 dB from pianissimo to fortissimo. That dynamic range increased to 16 dB in the youth choir and to 20 dB in the adult choir.

Ternström (1994) further investigated to what degree singers preferred to match their level to other choral members in a live choral performance. The investigation was then extended to a simulated choral environment (Ternström, 1999) in which the singers were able to dynamically control the ratio of their level to that of their colleagues. Results indicated that the singers’ preferred self-to-other ratio (SOR) varied considerably between subjects, ranging from –1 to +15 dB. However, individual singers maintained their own SOR with remarkable consistency, typically within ± 2 dB.

Lamarche *et al.* (2010) measured the voice range profile (VRP) of each of 30 female professional opera singers. In the first study of this scale, results indicated the need to differentiate between the *physiologic* VRP (a measure of the all the sounds the subject is capable of producing) and the *performance* VRP (a measure of the sounds the subject is willing to perform). While the maximum sound pressure level (SPL) produced did not appear to differ between the physiologic and performance VRPs, the size of the VRP area above 90 dB (the useable dynamic levels across frequency) increased in the performance VRP. The mean SPL range over fundamental frequency, calculated as the average difference in dB between the upper and lower limits of the

^{a)}Also at: Department of Communication Sciences and Disorders, The University of Iowa, Iowa City, IA 52242, USA. Electronic mail: ingo.titze@utah.edu

profile, differed significantly between the physiologic VRP and the performance VRP. Overall, the SPL range dropped from a mean of 27.38 dB in the physiologic VRP to 17.35 dB when subjects were cued to stay within their “performance-mode” in the performance VRP.

Geringer (1992) conducted an analysis of the dynamic contrast in commercially-produced recordings of choral, orchestral, and piano performances. No differences were identified in the magnitude of dynamic range between the performance medium (piano, orchestra, or chorus). However, across all three media, dynamic contrast was significantly dependent on the direction of dynamic change (crescendo vs decrescendo), with greater dynamic range exhibited during a crescendo (on average 13.42 dB) than during a decrescendo (on average 11.97 dB). However, the study investigated only changes from *p* to *f* (or vice versa) that were clearly indicated in the score. Consequently, little was illuminated regarding the full capability for dynamic contrast that may have been produced by *pp* to *ff* or greater changes. On a *messa di voce* exercise (a crescendo followed by a decrescendo), Titze *et al.* (1999) found that highly trained singers tended to shorten the duration of the decrescendo with respect to the duration of the crescendo. Some singers produced a 45 dB range of SPL in their *pp* to *ff* dynamic range.

Marshall *et al.* (1978) described concert hall acoustic conditions desirable for choral ensemble singing. The authors hypothesized that, as opposed to solo singing, ease of ensemble singing was dependent more on “early reflections” of sound and less on reverberation. By simulating a range of acoustic reflections relative to a stationary singer, it was found that singers strongly preferred reflection delays between 17 and 35 ms. In a second experiment, the spectral content of the reflections was investigated, indicating a preference for the presence of high-frequency content in the reflected sound. High-pass filtered, or unfiltered reflections were preferred nearly unanimously to low-pass filtered reflections.

Daugherty (2003) examined the preferences of both chorus members and listeners regarding spacing of the choir members in terms of the overall choral sound. In his study, 100% of the singers indicated that they felt that the spacing of the choir had some effect on the resultant choral sound, with 60% of singers preferring a configuration that allowed for approximately a 24 in. space between themselves and the next closest singer in all directions (circumambient spacing). Auditors also preferred the recordings made with the choir in a “spread formation” such as the circumambient spacing.

The purpose of this study was to parse out the three components available for building a large sound level range of a choir, (1) individual VRPs of the singers, (2) the full or partial use of these ranges when choral blend is a priority, and (3) the possibility for dynamic recruitment of voices within a performance. It is noted again that the use of sound level, the physical quantification of sound output, is not the complete description of perceived loudness, which depends on the sound spectrum in addition to sound level. The psychophysical analysis is left for a later study.

II. METHODS

The VRPs of five male singers and five female singers were obtained in a laboratory setting. The singers all had college-level personal training and had all sung in a choir in college or church. The VRP is a standard assessment tool in voice clinics and studios to determine the physiologic range of SPL a vocalist can produce over a wide range of fundamental frequency (f_o).

A. Equipment and environment

Recordings were made in two locations. Six subjects were recorded in the official voice therapy room at the Department of Communication Sciences and Disorders at the University of Iowa, while an additional four subjects were recorded in the research therapy room at the National Center for Voice and Speech at the University of Utah. A noise floor at or below 45 dBC was noted for each recording, ensuring that the lowest intensity recorded (above 50 dBC) for each subject was not influenced by environmental noise. SPL was recorded 30 cm from the subject’s mouth using a Brüel & Kjær (2238 Mediator) sound level meter. An experimenter observed the digital readout of the SL meter over at least 2 s of a sung /a/ vowel. A more precise measurement would have included a computer average of an electronic output, but a ± 1 dB accuracy obtained from the visual read-out was sufficient for this study. Pitches were cued to the subject using either an acoustic piano (U. Iowa) or an electronic keyboard (NCVS), both tuned to $A_4 = 440$ Hz.

B. Procedure and instructions

The following range of notes was cued, but the subjects chose only the notes they felt comfortable singing for durations on the order of 2–5 s, thus establishing their useful choir f_o range: C2 (65 Hz), E2 (82 Hz), G2 (98 Hz), C3 (131 Hz), E3 (165 Hz), G3 (196 Hz), C4 (262 Hz), E4 (330 Hz), G4 (392 Hz), C5 (523 Hz), E5 (659 Hz), G5 (784 Hz), C6 (1047 Hz), E6 (1318 Hz), G6 (1568 Hz). Pitch cues were varied in a quasi-random fashion, avoiding repeated phonations near either extreme of the subject’s voice range. After a pitch cue was given by the researcher, the subject produced their softest steady phonation. The same pitch was cued again and the subject produced their loudest phonation that felt comfortable. This process was repeated in the quasi-random order until the useable pitch range had been exhausted.

C. Analysis and simulation

A choir voice range profile was simulated by assuming that each singer is an independent (incoherent) sound source based on random phase. This allowed the intensities of the singers to be added linearly if the distance from each singer to a microphone or the distance to a listener is the same. Each singer will produce an intensity

$$I = I_o 10^{(SL/10)}, \quad (1)$$

where I_o is the reference intensity (10^{-12} W/m²) and SL is the sound level of a given singer at a given f_o and a common

FIG. 1. (Color online) VRPs of (a) five male singers and (b) five female singers. Solid lines are for loud notes and dashed lines are for soft notes.

distance. An average VRP was produced for both males and females. From this average VRP, a *choir section VRP* of males in a two-octave range was simulated. Parametric variations of the simulated choir VRP were then conducted to determine which factors provide the greatest dynamic range. The procedure was assumed to apply to all choir sections separately in a soprano-alto-tenor-bass (SATB) choir. While the spectra and VRPs may differ across voice classifications, the approach to summation of sound intensity is the same if a common frequency range can be determined.

III. RESULTS

Figure 1 shows overlays of the VRPs of 5 male singers and 5 female singers. Collectively, both males and females cover an f_o range of about 3 octaves and an SPL range of 30–40 dB, but there is considerable variation across singers. At the extreme frequencies, the high intensities of some singers overlap with the low intensities of others. The female singers were more variable in their mid-frequencies, particularly in the 600–800 Hz range. As has been reported in all VRP studies, there is a general increase in SPL with f_o , here on the order of 50 dB in the 50–1000 Hz range. This increase comes from two factors, (1) the greater sound radiation

efficiency with higher f_o (about 6 dB per octave because radiated power varies with the square of frequency for a sinusoidal component) and (2) the greater lung pressure used by singers at higher f_o , which increases the peak acoustic flow.

Figure 2 shows averaged VRPs over a two-octave range for both male and female singers. A two-octave range is generally sufficient to cover the f_o range of a choir section. A second-order (parabolic) fit is also shown, which was used as a model for simulated VRPs to be described below. The two-octave range was covered by all singers, so that the average had the same number of data points at each frequency. Note that the males had a dynamic range of more than 25 dB over most of the two octaves, whereas the females had a dynamic range of more than 20 dB over their two octaves. For both genders, the lowest intensity was 70 dB near the bottom of the f_o range and the highest intensity was 113 dB near the top of the f_o range.

The curve-fitted data provided an opportunity to simulate an ensemble voice range profile with some controllable parameters. Figure 3 (left panel versus right panel) shows the variation of overall SPL and dynamic range of SPL with a large difference in choir section size, 16 per section versus 128 per section. The SPL values were re-calculated from a 30 cm distance in the recording studio to a 20 m distance in a

FIG. 2. (Color online) Averaged VRPs over a two octave range of (a) five male singers and (b) five female singers. Solid lines are second order curve fits.

FIG. 3. (Color online) Simulated VRPs for a male choir section in a two-octave tenor range. The distance to the listener is 20 m. (a) medium choir size with 16 per section (b) large choir size with 128 per section. Dashed lines are for a reduction to 1/8 of the section size.

concert hall location. With an eightfold increase in section size, the overall SPL increased a mere 9 dB. This result is well-known. Every doubling of the source power increases the sound level by 3 dB. There is no corresponding increase in dynamic range. In both cases, the dynamic range was 28 dB, but it could be increased by 9 dB if only 1/8 of the section were to sing the soft notes (dashed lines). The 28 dB range allows steps of 5.6 dB per dynamic level increase (*pp-mp-mf-f-ff*), which is well above the 1–2 dB just noticeable difference (JND) in a free-field environment (Howard and Angus, 2006). The 37 dB dynamic range with a reduction of singers from 16 to 2 per section allows steps of 7.4 dB per dynamic level increase (a 10 dB step is a doubling of loudness at 1000 Hz), but the concert hall must have a noise floor low enough to allow 1/8 of the singers to be heard. For the 16 per section choir, this suggests a 37 dB ambient noise floor for two singers to be heard at a 20 m distance. For the 128 per section choir, a 45 dB noise floor allows 16 singers to be heard at their lowest (*pp*) level at 20 m. However, this calculation is based on free-field acoustics, which does not include any advantage received from reflections in the hall.

The simulation with identical singers represents a perfect choir blend. Many choral conductors seek a choir blend to some degree, not only in terms of loudness across singers, but also in terms of pitch, vowel, vibrato, and sound timbre.

Only loudness blend is under consideration here. The increase in the dynamic level can be obtained by summing up the intensities of the fraction N of the section singing X dB louder or softer than the remaining $1-N$ fraction of singers. The result is

$$\Delta SL = |10 \log_{10}(1 - N + N * 10^{X/10})|. \quad (2)$$

Note that when $N = 0$, $\Delta SL = 0$, and when $N = 1$, $\Delta SL = X$. Figure 4(a) shows how the dynamic range of a choir section changes with a gradual increase in the percentage of softer-than-normal voices. Three curves are shown, for which the bottom of the individual VRP in Fig. 1 was shifted downward from the average by $X = -5$ dB, $X = -10$ dB, and $X = -15$ dB. For the -5 dB downward shift (some singers being able to sing -5 dB softer than others), it takes 90% of the section to be soft voices in order to gain an overall 4.1 dB increase in the dynamic range of the section. With a -10 dB downward shift, these 90% soft voices produce only a 7.21 dB gain, and with a -15 dB downward shift, this large group of soft voices produce a 9 dB gain.

The situation is quite different when loud voices are added to a section, as shown in Fig. 4(b). If only 20% of the voices are louder by $+5$ dB, the net dynamic gain of the section is slightly under 2 dB. If the same 20% are $+10$ dB

FIG. 4. (Color online) Increase in dynamic range with non-homogeneous voices in a two-octave tenor range. (a) Change in SPL with percent softer voices, (b) change in SPL with percent louder voices.

stronger, the section gain is 4.5 dB, and if the same 20% are 15 dB stronger, the section gain is 8.5 dB. The result suggests that a few loud voices can dominate the loudness of a group, but a few soft voices do not dominate the softness of a group.

IV. DISCUSSION AND CONCLUSIONS

The dynamic range of a choir, described in written music with a set of markings [*pp-p-mp-mf-f-ff*], has been quantified here in terms of steps of SPL increases. The JND of SPL levels in a free-field environment is on the order of 2 dB (Howard and Angus, 2006). Taking 3 dB as a distinguishable level difference for most listeners, a choir voice range profile should show a range of at least 15 dB between the softest (*pp*) and loudest (*ff*) notes over a wide frequency range (about 2 octaves per choir section). The singers chosen for this study were all vocally trained, exhibiting an average SPL range of 20–25 dB over a two-octave f_0 range. From these ranges, it was predicted that an ensemble of 64 of these singers performing at a distance of 20 m from the listener would produce a maximum sound level of about 90 dB at high frequencies and a minimum level of about 50 dB at low frequencies. Taken at each f_0 separately, the dynamic range averaged 28 dB for males over two octaves between C3 and C5. Dynamic ranges for females were slightly smaller, but also above 20 dB throughout a two-octave range (C4–C6). The 28 dB range would allow choir sections to take five discrete 5.6 dB steps to cover all the dynamic markings. Perceptually, a doubling of loudness requires 10 dB steps at 1000 Hz.

For a homogeneous choir (all singers singing equal loudness and having equal loudness variation), choir size has no bearing on dynamic range. A thousand voices, each with a 15 dB range, will produce a choir dynamic range of only 15 dB if all singers sing all notes. The overall sound level of the choir increases by 3 dB for every doubling of size. Thus, increasing the choir size from 16 to 32 adds only 3 dB, from 32 to 64 adds another 3 dB, and from 64 to 128 adds another 3 dB. A relatively large choir, like the Mormon Tabernacle Choir with 360 voices, has an overall sound level only 9 dB greater than a 45 voice choir with similar voices. Thus, from the standpoint of economy, there is a point of diminishing return with choir size. The main motivation for choosing a large choir is the involvement of more people and the visual appearance of a grandiose production.

Regardless of choir size, the dynamic range can be increased by reducing the number of singers dynamically. Obviously, this makes only the soft sounds softer, a strategy useful in small performance halls in which a few singers per section can be heard in all seats. Every factor of 2 reduction in the number of singers emitting sound increases the dynamic range by 3 dB. Thus, only 4 people singing in a choir section of 16 will buy 6 dB, two extra levels of loudness to produce *ppp* and perhaps even *pppp* dynamics.

An unexpected result is the degree to which a few skilled singers with large VRPs can affect the dynamic range

of a choir. It has been shown that professional singers can have a 30–40 dB SPL range over much of their f_0 range. This exceeds the typical range of amateur or semi-professionals singers by 15–20 dB. The current results show that 1 out of 5 such singers per section can increase the entire dynamic range of the choir by 5–15 dB on loud notes, roughly the equivalent of multiplying the entire amateur choir size by 16 for these dramatic notes. This result is a clear indication that vocal training and inclusion of gifted singers in a choir is a far better solution for enhanced dynamics than adding more singers with a small range. The counter-argument is that choir blend may suffer. If the gifted singers are asked to sing mostly *mezzo voce* to blend with their neighbors, they will feel constrained and vocally unsatisfied. In this case, a choral director can give them license to sing only on the loud part of the dynamic spectrum. Muscle physiology uses this tactic. Large motor units are recruited only for maximal contractions, while small motor units deal with the more delicate contractions. A somewhat similar situation exists with regard to pitch range. In Russian choral music, the very low basses are sometimes selectively recruited only for their low notes.

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- Coleman, R. F. (1994). "Dynamic intensity variations of individual choral singers," *J. Voice* 8(3), 196–201.
- Daugherty, J. F. (2003). "Choir spacing and formation: Choral sound preferences in random, synergistic, and gender-specific chamber choir placements," *J. Res. Choral Sing.* 1(1), 48–59.
- Gauffin, J., and Sundberg, J. (1980). "Data on the glottal voice source behaviour in vowel production," *Speech Transmission Laboratory—Quarterly Progress and Status Report (STL-QPSR)* KTH, Stockholm, Sweden, Vol. 203, pp. 61–70.
- Gauffin, J., and Sundberg, J. (1989). "Spectral correlates of glottal voice source waveform characteristics," *J. Speech Hear. Res.* 32, 556–565.
- Geringer, J. (1992). "An analysis of dynamic contrasts in recorded choral, orchestral, and piano performances," *Bull. Council Res. Music Edu.* 112, 51–61.
- Howard, D. M., and Angus, J. A. S. (2006). *Acoustics and Psychoacoustics*, 3rd edition (Focal Press, Oxford, UK), pp. 97–98.
- Lamarque, A., Ternström, S., and Pabon, P. (2010). "The singer's voice range profile: Female professional opera soloists," *J. Voice* 24(4), 410–426.
- Marshall, A. H., Gottlob, D., and Alrut, H. (1978). "Acoustical conditions preferred for ensemble," *J. Acoust. Soc. Am.* 64(5), 1437–1442.
- Rossing, T. D., Sundberg, J., and Ternström, S. (1986). "Acoustic comparison of voice use in solo and choir singing," *J. Acoust. Soc. Am.* 79(6), 1975–1981.
- Ternström, S. (1993). "Long-time average spectrum characteristics of different choirs in different rooms," *Voice (UK)* 2, 55–77.
- Ternström, S. (1994). "Hearing myself with the others—Sound levels in choral performance measured with separation of the own voice from the rest of the choir," *J. Voice* 8(4), 293–302.
- Ternström, S. (1999). "Preferred self-to-other ratios in choir singing," *J. Acoust. Soc. Am.* 105(6), 3563–3574.
- Ternström, S. (2003). "Choir acoustics: An overview of scientific research published to date," *Int. J. Res. Choral Sing.* 43, 1–8.
- Titze, I. R., Shirley, G., Long, R., Stathopoulos, E., Ramig, L., Carroll, L., and Riley, W. (1999). "Messa di voce: An investigation of the symmetry of crescendo and decrescendo in a singing exercise," *J. Acoust. Soc. Am.* 105(5), 2933–2940.