Supporting Information for

Closed-Loop Network of Skin-interfaced Wireless Devices for Quantifying Vocal Fatigue and Providing User Feedback

Hyoyoung Jeong, Jae-Young Yoo, Wei Ouyang, Aurora Lee Jean Xue Greane, Alexandra Jane Wiebe, Ivy Huang, Young Joong Lee, Jong Yoon Lee, Joohee Kim, Xinchen Ni, Suyeon Kim, Huong Le-Thien Huynh, Isabel Zhong, Yu Xuan Chin, Jianyu Gu, Aaron M. Johnson, Theresa Brancaccio*, and John A. Rogers*

* Corresponding author: John A. Rogers

Email: jrogers@northwestern.edu

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Supporting Information Text

Quantifying the performance of the adhesives. A Mark-10 Force Gauge enabled comparisons of peel forces of four different adhesives on the skin. Similar measurements determined the forces for removing the sensors from the magnetic adhesive when attached to the skin. *SI Appendix*, Fig. S5 shows an image of the four adhesives tested: hydrogel, magnetic adhesive, fabric-based tape with MED6500 adhesive, and the medical silicone adhesive. Peel forces are shown in *SI Appendix*, Fig. S6. Removing the device from the magnetic adhesive and the hydrogel required the lowest maximum peel force. The sharp steps in the force graph for removing the device from the magnetic adhesives resulted from the device detaching sequentially from each magnet. The magnetic adhesive with fabric-based tape for the skin interface demonstrated a moderate maximum peel force and slope. The medical silicone adhesive (3M, 2477P) and the fabric-based tape coupled with the MED6500SI adhesive had the highest maximum peel forces and greatest initial slopes. *SI Appendix*, Fig. S7 shows images of a participant's skin at the suprasternal notch area to compare redness at three time points (twenty minutes, forty minutes, and sixty minutes) after adhesive removal. The images demonstrate decreasing redness of the skin from moderate at twenty minutes to none at sixty minutes. The results of adhesive validation testing indicate that most users found the adhesives easy to use and comfortable. Based on these results, the adhesive comprised of fabric-based tape coupled with a MED6500 adhesive was chosen as the adhesive for continuous monitoring for at least a day at a time.

Verifying calculated vocal dose and perceived effort. In studies to verify that the vocal dose algorithm aligned with perceived effort, four singers (soprano, alto, tenor, and baritone) recorded a set of known tasks. The tasks included normal speaking, speaking over 60 dB SPL of ambient noise, whispered speaking, moderate singing (low to mid-range), moderately loud singing (mid to high range), loud singing (low to mid-range), very loud singing (mid to high range), singing without vibrato (low to mid-range), staccato arpeggios throughout the vocal range, and strained speaking. Participants rated their perceived vocal effort on a scale from one to ten (1 = no effort, 10 = maximum effort). Each task was recorded for one minute with one minute of rest in between.

Aligning sensor data with self-reported activities. Sixteen university singers, seven male and eight female wore the MA device affixed just below the suprasternal notch and recorded all of their daily vocal use. The singers wore the devices for between one day and five consecutive days, removing them only to shower and sleep. Each simultaneously recorded their activities and self-assessments on various surveys throughout each day. Each participant began and ended the day with vocal fold “Swelling Check” exercises as a barometer of vocal function (1). The exercises expose vocal fold mucosal swelling through singing quietly in the topmost part of their vocal range. The highest pitch that the participant could no longer phonate clearly and softly defined the “ceiling pitch”. Participants reported the number of hours they slept along with their perceived quality of sleep, and their morning ceiling pitch in a survey each day. Their morning swelling checks were additionally recorded in a voice memo as a WAV file and uploaded to a cloud drive. Throughout the day, participants completed multiple brief surveys, documenting the start and end time of each unique vocal activity, as well as their perceived vocal effort for said activity. These activities included speaking, solo singing, choral singing, quiet time, teaching, opera rehearsal and an option to specify a type of activity that was not already listed. Every evening, at the completion of the day's activities, participants performed both swelling checks and recorded the results in a voice memo, reported their ceiling pitch in a survey, and then removed the device. The data was then downloaded from the device to the smartphone.

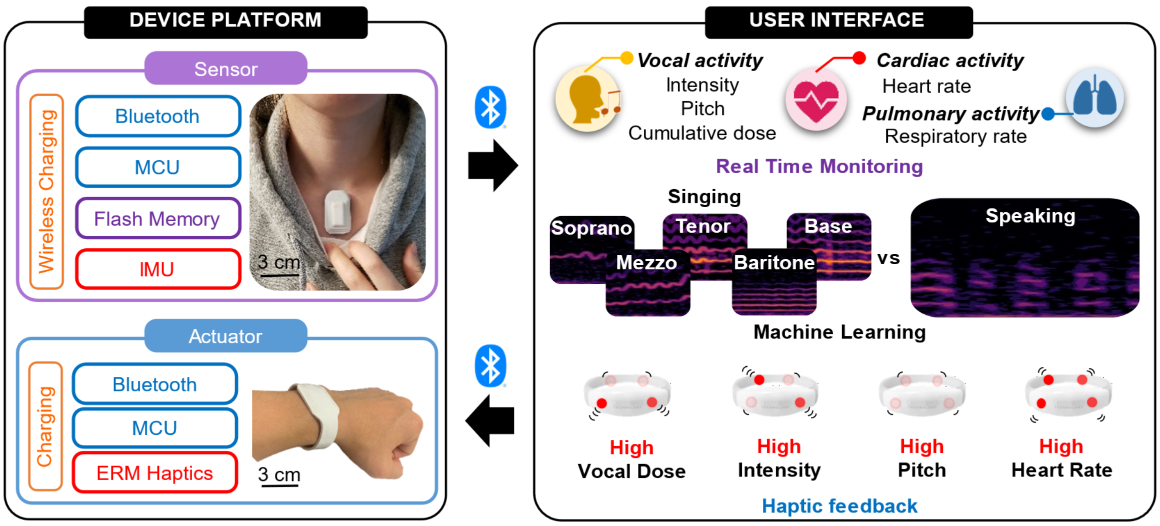


Fig. S1. An illustration of the overall platform operation including sensor, user interface, and feed-back actuator.

Fig. S2. Devices packaged in various colors to promote user identification of devices on the mobile application.

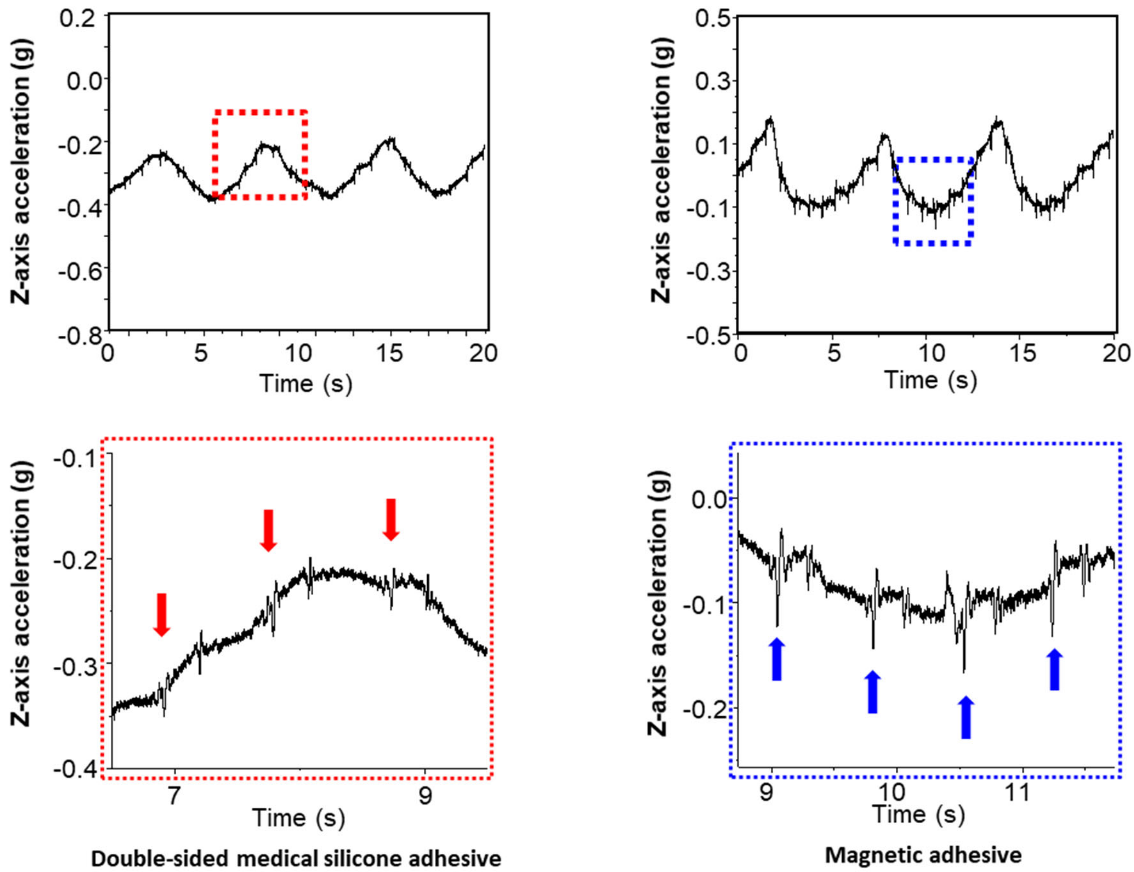


Fig. S3. Data collected using different adhesives during trials with subjects at rest. The bottom graphs are magnified sections of the top graphs to show that seismcardiogram signals are detectable using both adhesives.

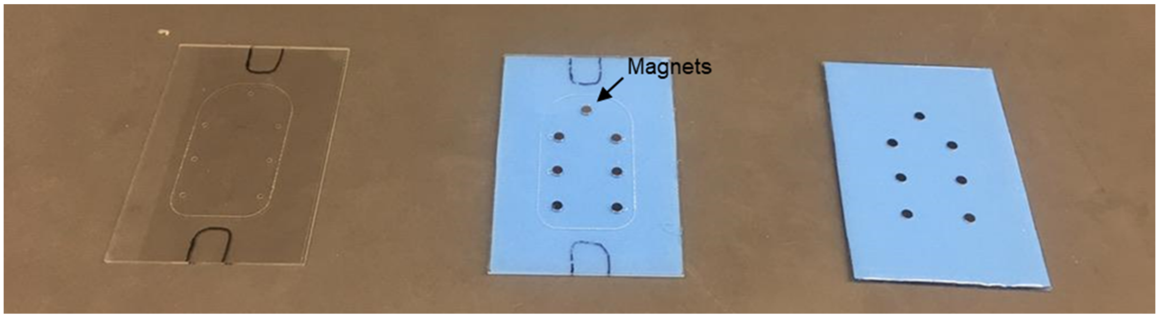


Fig. S4. Fabrication of the bottom encapsulation layer of the device with magnetic adhesives.

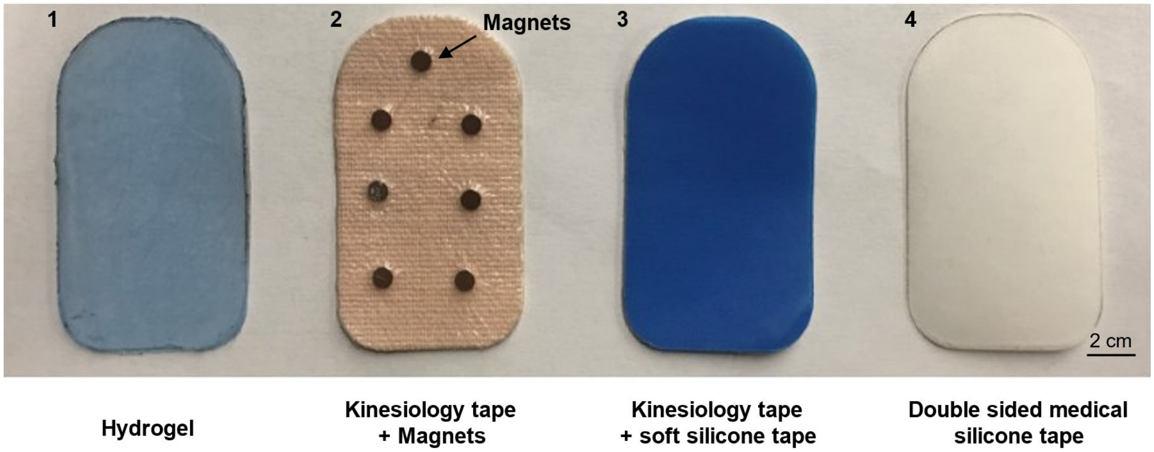


Fig. S5. Various adhesives tested for skin comfort and redness after removal. The leftmost adhesive is a hydrogel tape (KM 40A, KATECHO) alone. The second from the left is a combination of kinesiology tape (SpiderTech, Nitto Denko) and magnets sealed with Tegaderm (3M). The second from the right is a combination of kinesiology tape and a soft silicone adhesive (MED6500SI, Avery Dennison). The rightmost adhesive is the medical silicone tape (2477P, 3M).

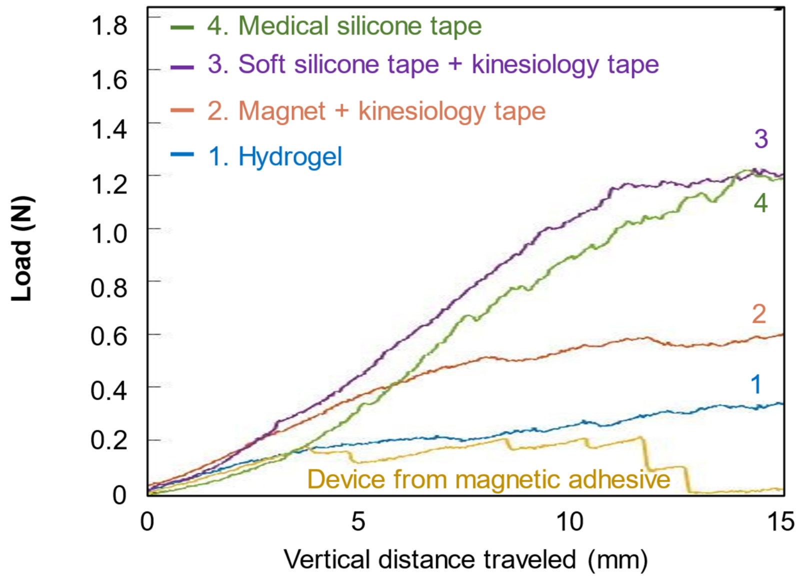


Fig. S6. Peel forces for four adhesives on the skin (labeled 1 to 4) and for removal of a device from the magnetic adhesive.

Fig. S7. Images of skin redness at three time points after adhesive removal.

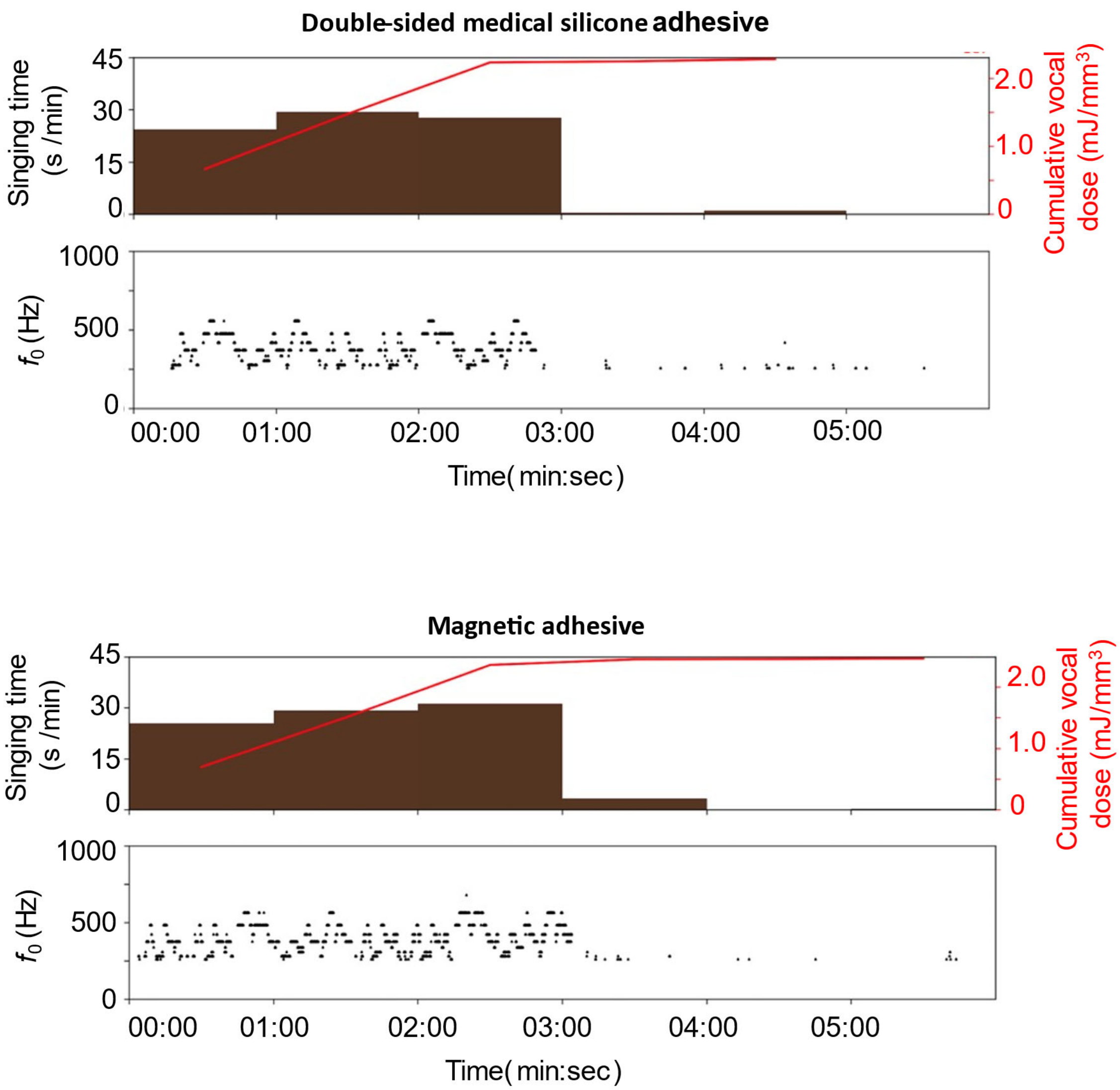


Fig. S8. Comparison of data collected from devices coupled to the body using a magnetic adhesive and a non-magnetic adhesive. Data from the two devices yielded similar values for singing time, cumulative dose, and fundamental frequency during three minutes of speaking and three minutes of singing.

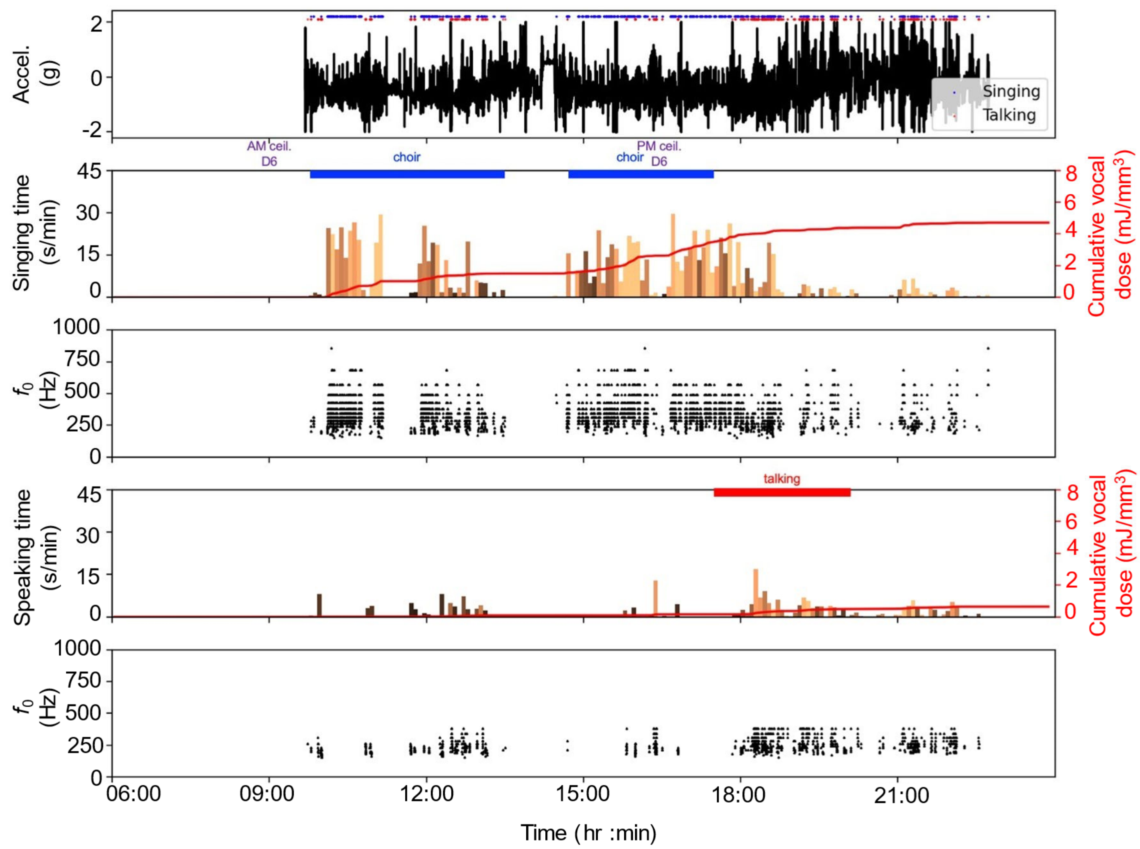


Fig. S9. Data from a mezzo-soprano with self-reported activities noted.

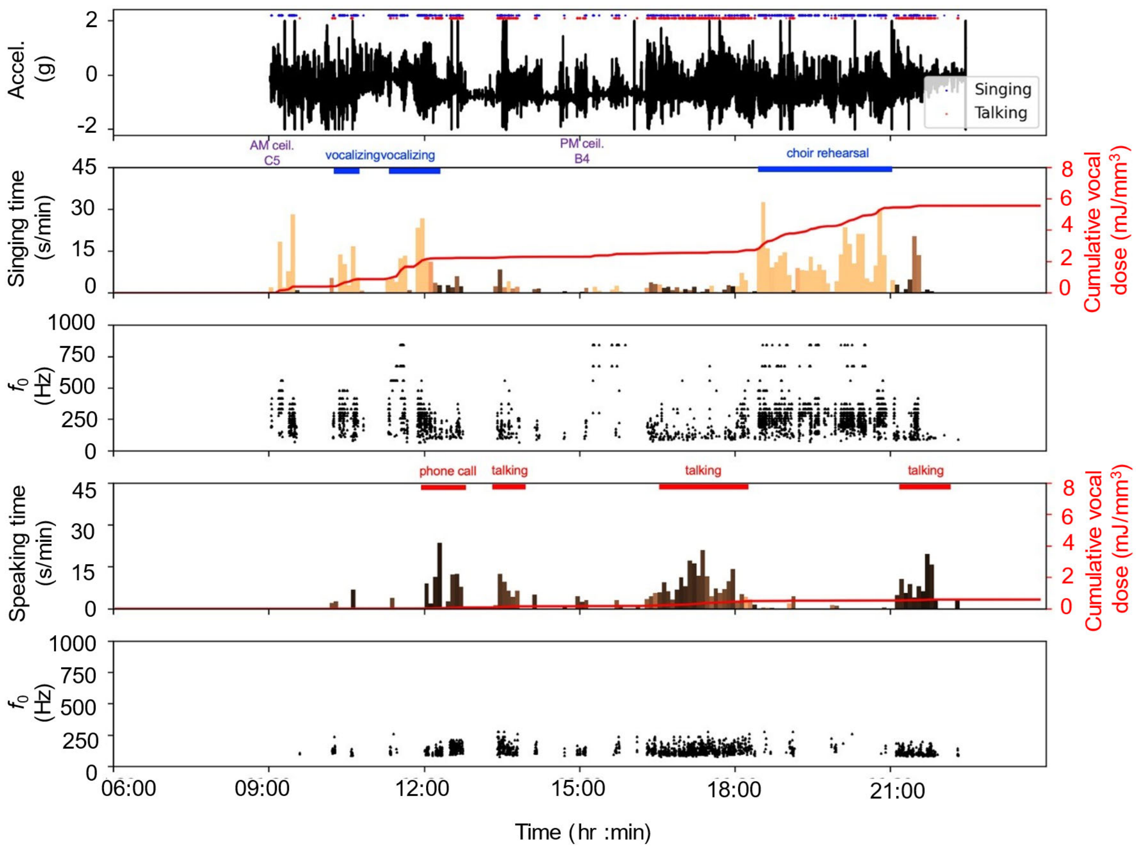


Fig. S10. Data from a tenor with self-reported activities noted.

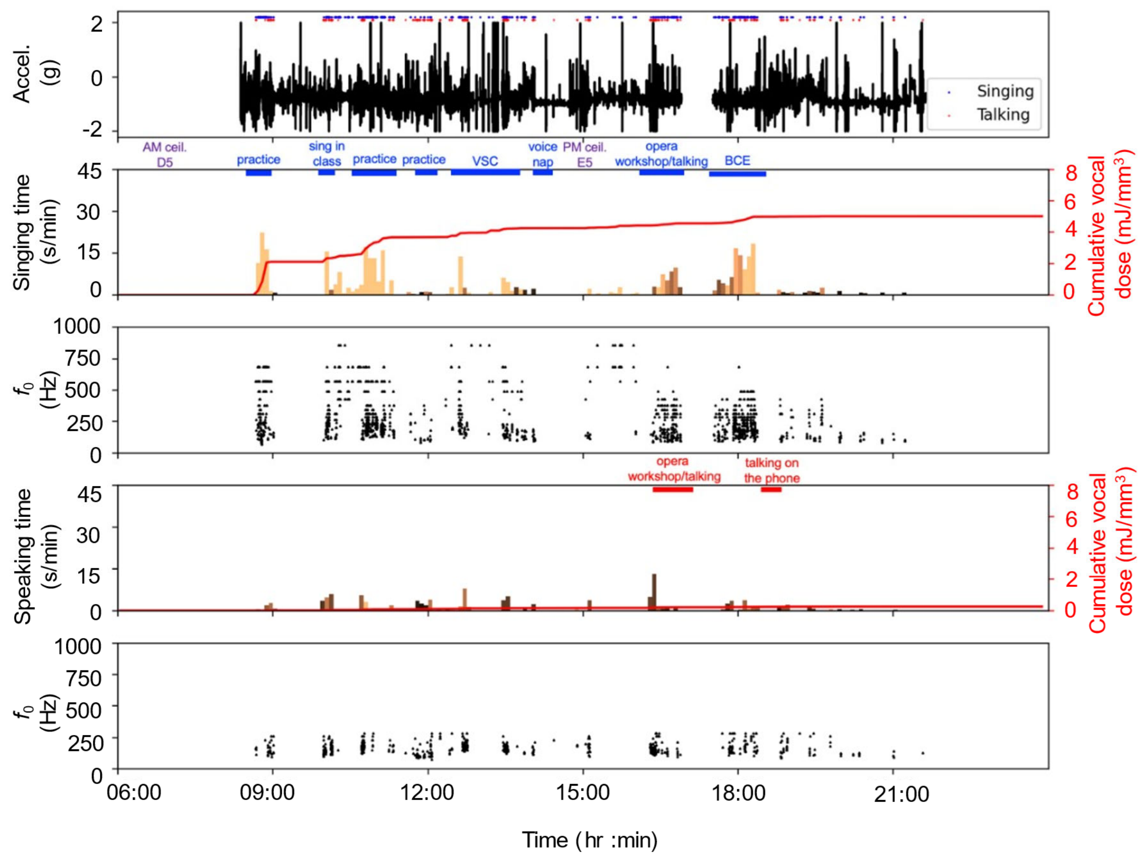


Fig. S11. Data from a baritone with self-reported activities noted.

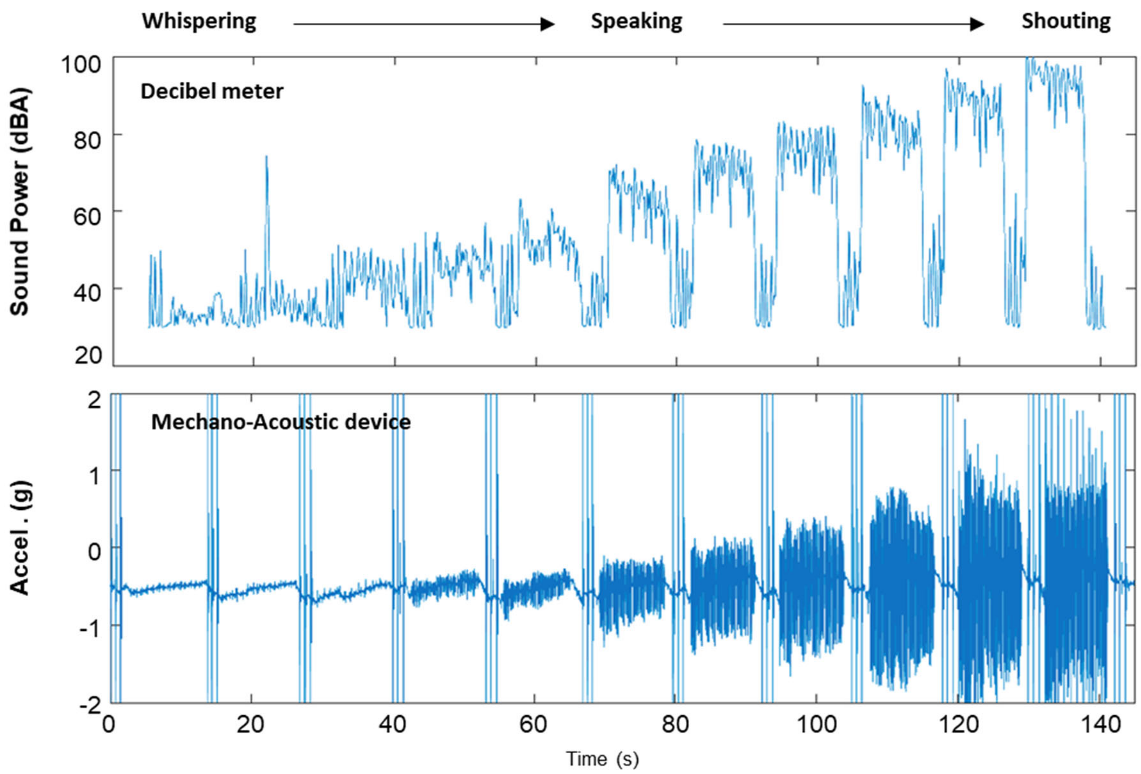


Fig. S12. Raw data for calibration of mechano-acoustic power and acoustic power. Note that the tapping signals between transitions causes saturated acceleration values.

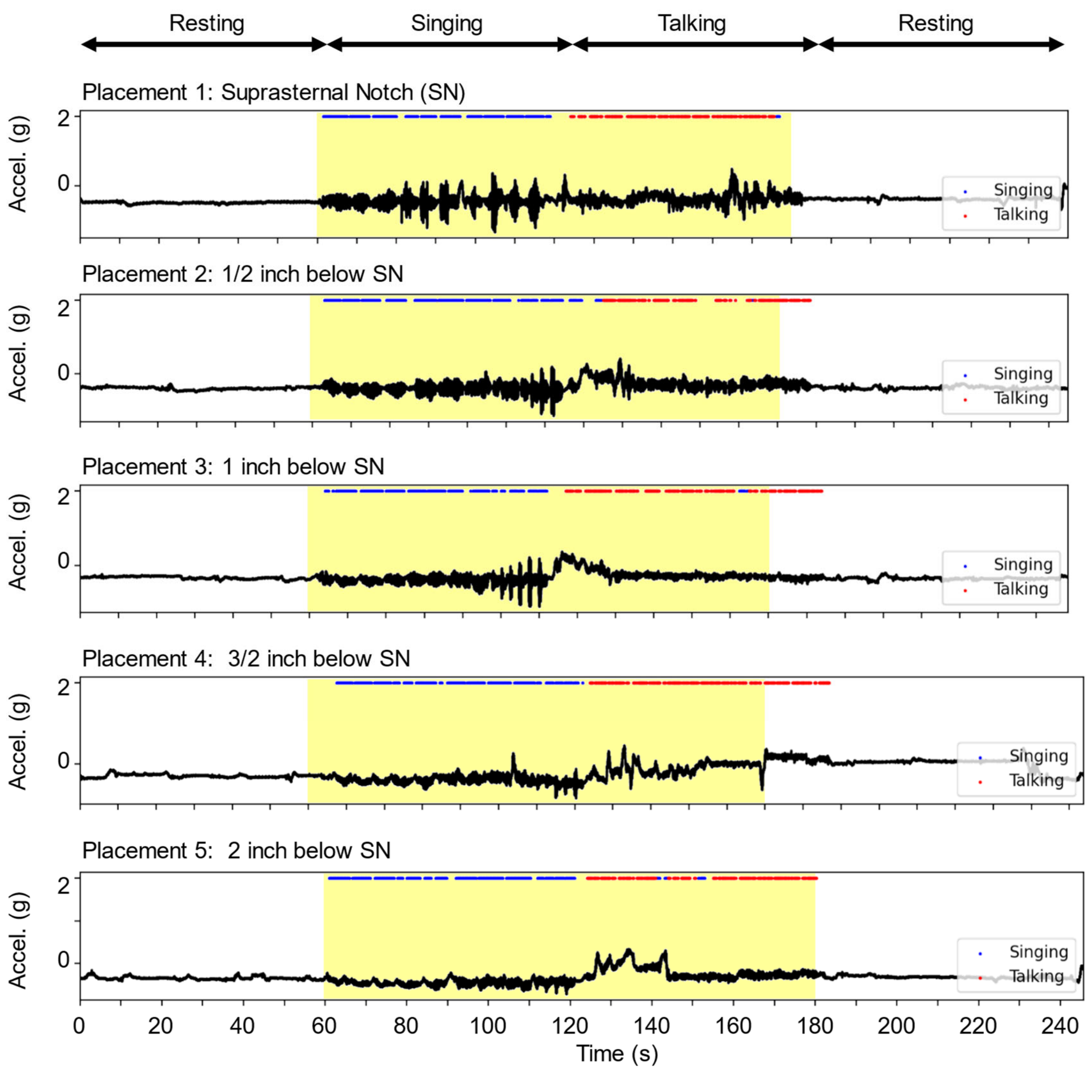


Fig. S13. Comparison of singing and speaking classification by the CNN model from the data collected with five different placements: suprasternal notch (SN), 0.5 inches below SN, 1 inch below SN, 1.5 inches below SN, and 2 inches below SN. Blue and red dot denotes classified singing and talking events.

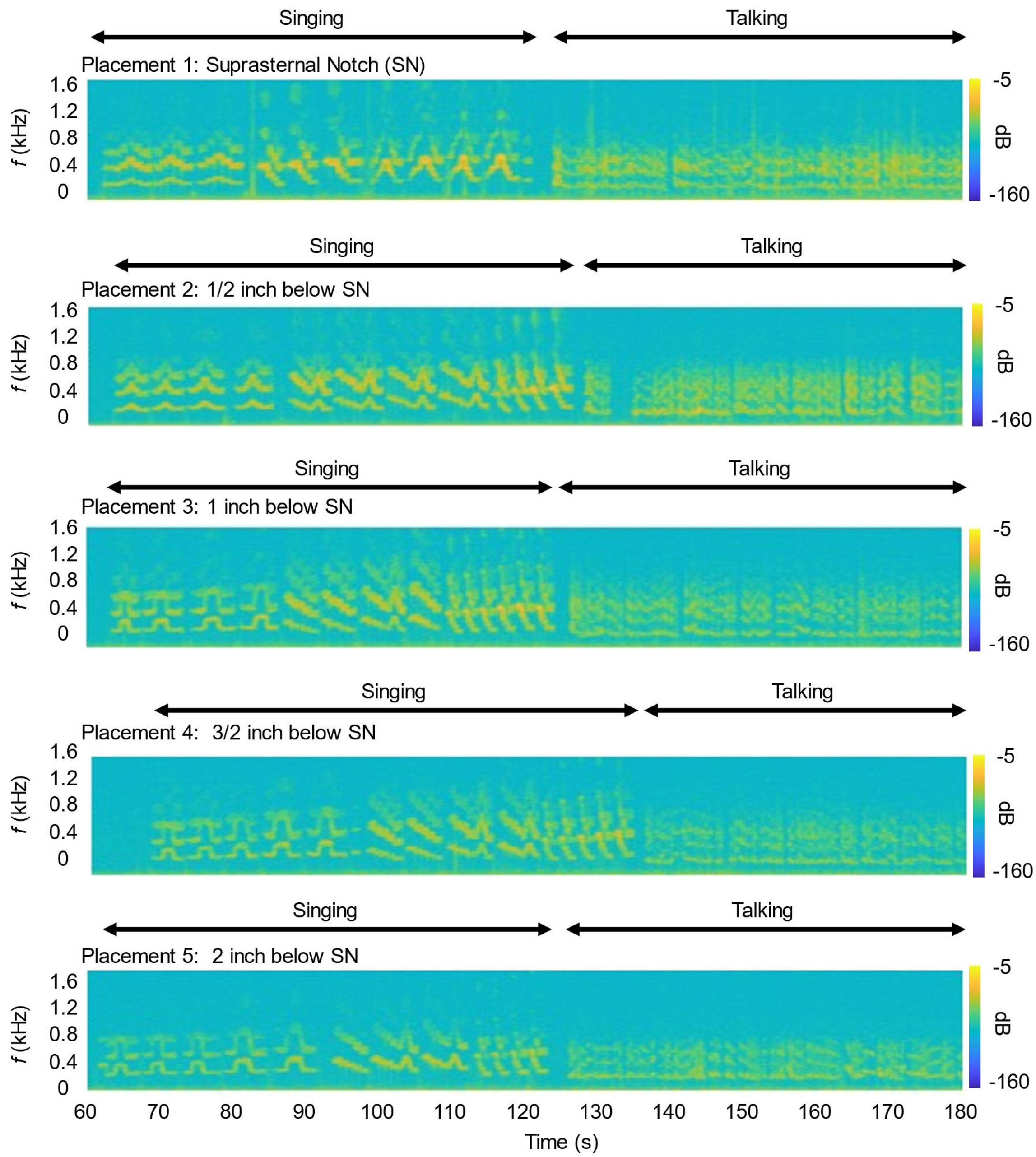


Fig. S14. Comparison of spectrograms for singing and speaking data highlighted in the data from Fig. S13

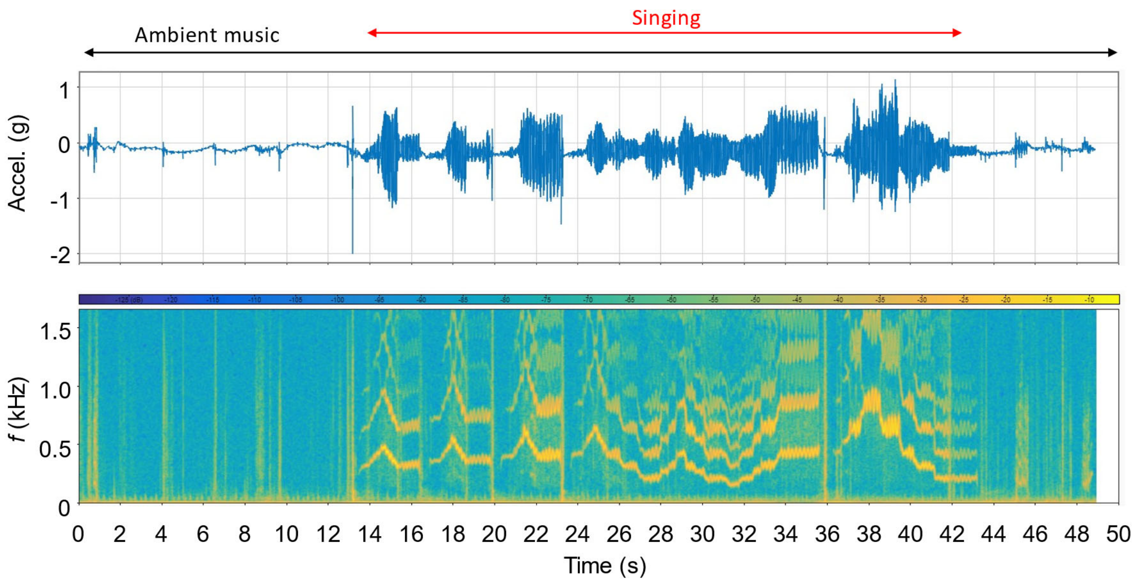


Fig. S15. Validation of interference by ambient noise. The subject wore an MA device on the upper chest. Data were collected with ambient loud music (Beethoven Symphony No. 9, 62 - 79 dBA range) while singing with different ranges of pitch.

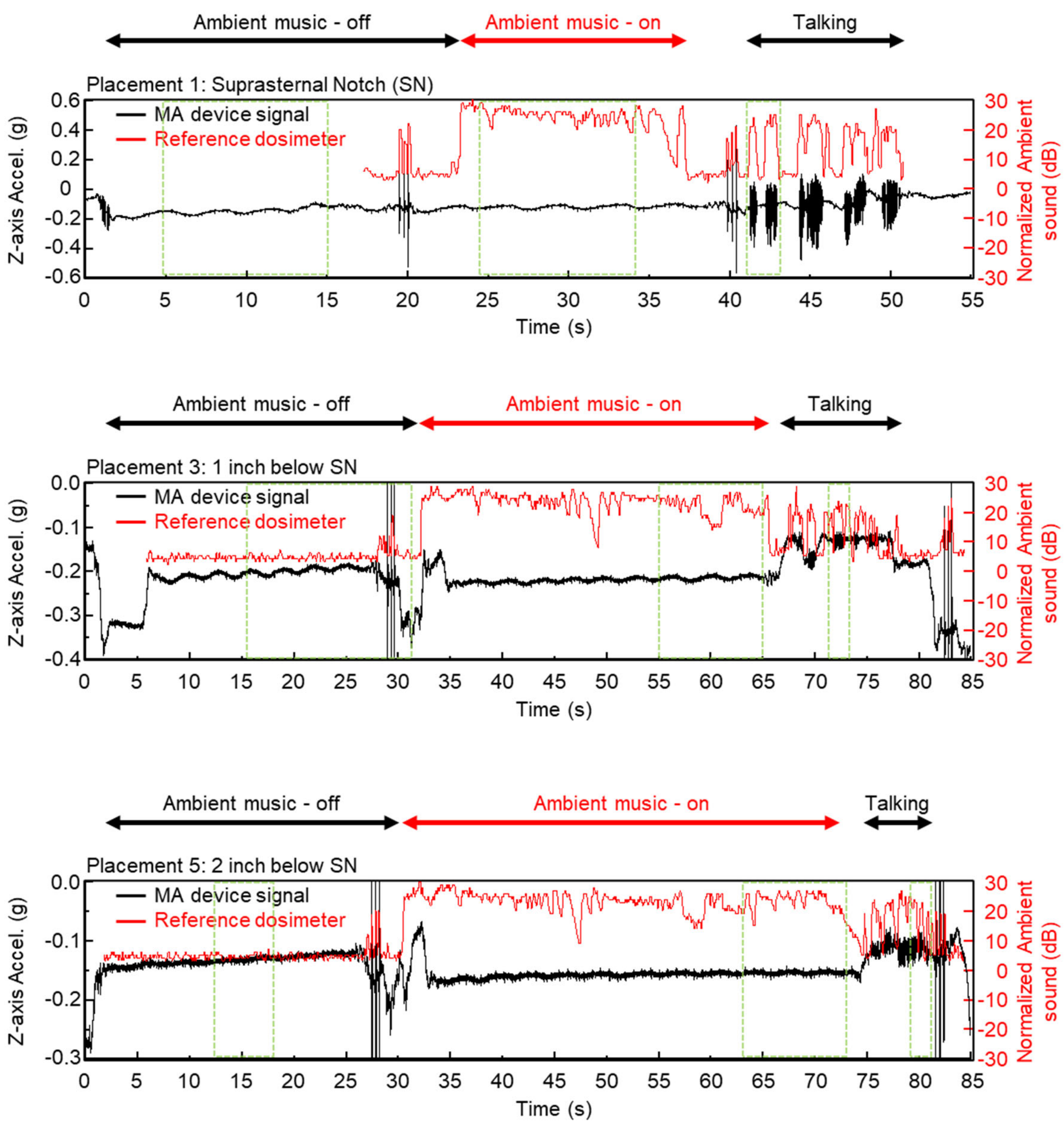


Fig. S16. Comparison of data collected in a noisy environment at three different locations including suprasternal notch (SN), 1 inch below SN, and 2 inches below SN.

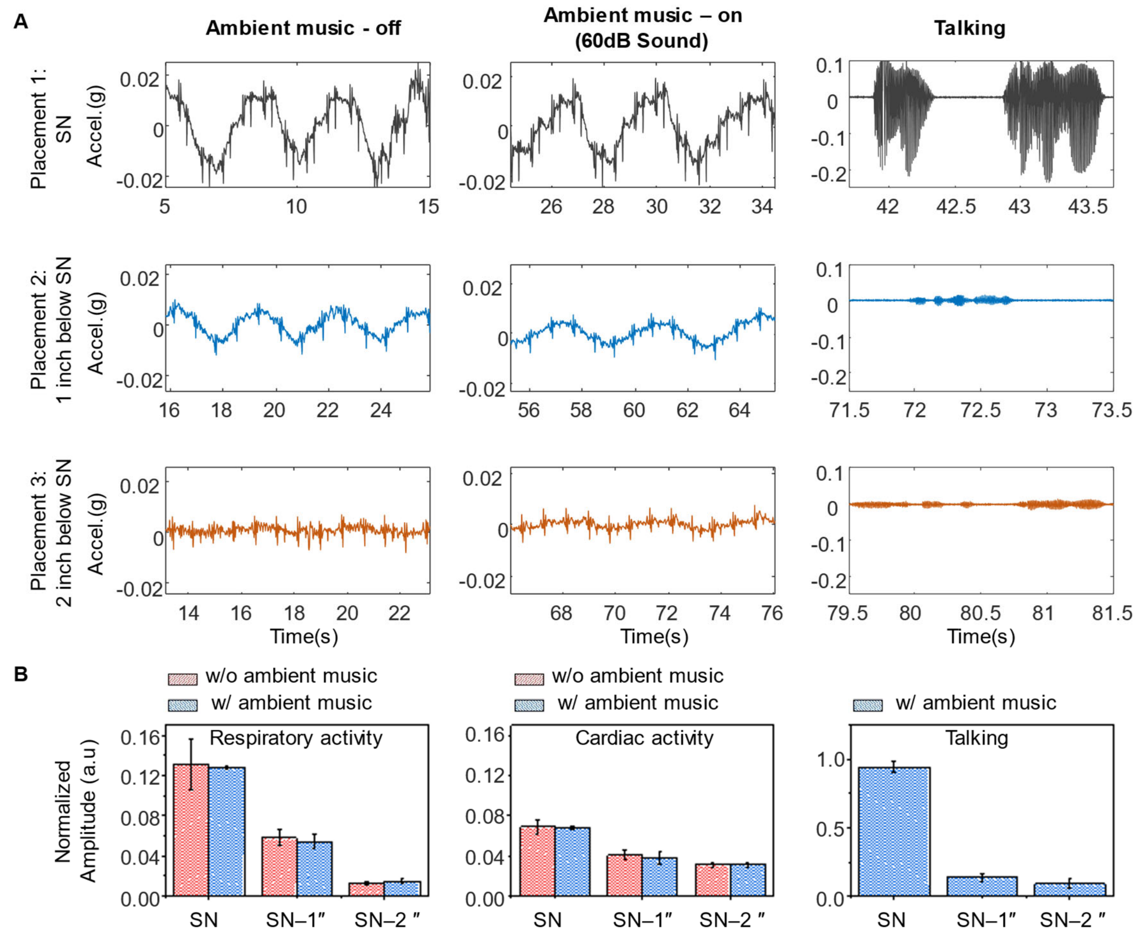
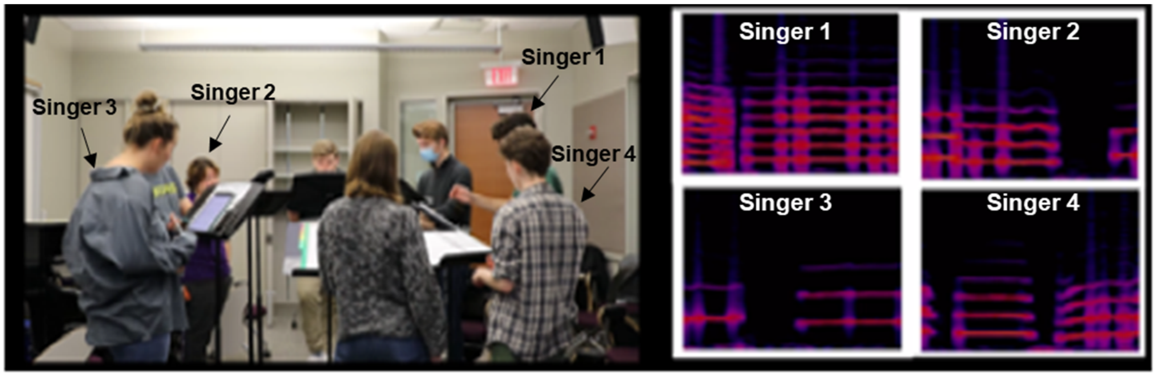


Fig. S17. Quantitative comparison of signal-to-noise ratio (SNR) collected in a noisy environment at three different locations including suprasternal notch (SN), 1 inch below SN, and 2 inches below SN. (*A*) Zoom-in signals from green region in Fig. S16. (*B*) Normalized signal amplitude from three different placements in terms of respiratory activity, cardiac activity, and talking signal after data processing.



Movie 1. Devices used in a choir rehearsal setting demonstrate the capacity to capture data from an individual singer without influence from vocalization by other singers. The studies involve four singers (one soprano, one alto, one tenor, and one bass) during a rehearsal, with devices paired with smartphones or tablets for real-time dosimetry calculations.

Audio 1. Validation of interference by ambient noise with converted audio. Converting the MA data (Fig. S15) to audio files confirmed that the influence of ambient music is almost negligible.

SI Reference

1. R. W. Bastian, A. Keidar, K. Verdolini-Marston, Simple vocal tasks for detecting vocal fold swelling. *J. Voice* **4**, 172–183 (1990).