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# Raising public awareness of acoustic principles using voice and speech production<sup>a)</sup>

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Public engagement with science, technology, and engineering is seen as being increasingly important as the numbers of school leavers choosing to read for degrees in these areas is typically dropping. Engagement with pupils during their school years is seen as being a key element in influencing their choices of career for which seeds are sown from the primary years. Acoustics is an excellent vehicle for public engagement since the demonstrations can be appreciated directly by the sense of hearing and the underlying principles also apply in many branches of physics and engineering. This paper describes a number of demonstrations that have been employed during science engagement events for schools and the general public in the context of the principles of acoustics and human speech production. The apparatus used, which in some cases has been purpose-built, is described along with the activities themselves. In addition, a way to quantify the success of the process is proposed that involves a single button press on entry to and exit from an event.

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## I. INTRODUCTION

The inspiration of the young to the field of science, technology, engineering and mathematics is very important for the future. Acoustics is a rich field in which to inspire people because you can hear the results of whatever experiment or activity you are carrying out. During my three years (2005–2008) as a Senior Media Fellow of the UK Engineering and Physical Sciences Research Council (EPSRC) I was involved in running activities such as workshops, lectures, and activity sessions for schools, colleges, and the general public as well as looking for opportunities for exposure in the media, whether written, radio or television. During the course of this Fellowship the following three words served to sum up the overall aim of the various activities: “awe,” “wonder,” and “amazement;” if a sense of these could be instilled in the minds of members of the audience then they have been hooked and they themselves will fill in later any underlying mathematics or other technical details.

Acoustics is at the heart of teaching and research activities in the Audio Laboratory at the University of York, UK and formed the basis of the activities, discussions and demonstrations designed and implemented during the Fellowship. This paper described a number of these activities under seven separate headings (Secs. II A to II G below) and it is offered as a resource for others offering acoustics education for the public. In each case, the key features of the demonstration, the apparatus used and the experimental procedures employed are described along with the underlying acoustic principles. All the demonstrations have been used with the general public and/or primary and secondary school pupils in the UK. Evaluation of the effectiveness of such activities is an important part of such work and a novel quantitative

assessment technique based on a single button press on entry and another on exit is described that was developed as part of the Fellowship.

## II. APPARATUS AND EXPERIMENTAL PROCEDURES

This section describes the apparatus used for each acoustic demonstration along with the experimental procedures employed. Some of the apparatus is very simple and makes use of readily available items, while some is rather more specialized and makes use of purpose-built or specially purchased equipment. In every case, the information provided should be sufficient to enable the demonstration to be repeated either as a direct replication or by taking the basic idea and making appropriate variations to the basic apparatus and experimental technique. The author is always happy to be contacted for further details.

### A. Sound communication over distance

Sound transmission over some distance in a situation with poor signal-to-noise ratio due to the presence of competing acoustic noise can be demonstrated using cheap plastic drinking cups and string. Participants work in pairs, each having a cup and a piece of string long enough to ensure that the pair are sufficiently far apart from each other so they cannot readily hear each other at normal conversational speech levels (a large hall is ideal for this demonstration). One participant is the speaker (the cup is placed over her/his lips) and the other is the listener (the cup over an ear) and each cup is attached securely to one end of the string (passing it through a hole and tying a paperclip on the end works well). The best result is achieved when least physical contact is made with the sides of the cups to reduce damping on the acoustic vibrations and when the string is taut to enable transverse wave sound transmission.

A written sentence is given to each speaker that is to be transmitted to the appropriate listener. If this is done as a

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83 group activity in a reverberant environment, the speakers  
 84 will tend to raise their voices possibly to the point of shout-  
 85 ing to be heard over the other speakers. There comes a point  
 86 where the cup and string communicator is redundant if the  
 87 overall sound level that is reaching each listener's ear is  
 88 dominated by high sound levels in the room itself. This pro-  
 89 vides an opportunity to discuss the potential for message or  
 90 data disruption over a communication channel due to compet-  
 91 ing noise and to introduce the notion of signal-to-noise ratio.  
 92 In addition, the acoustics of the room could be explored  
 93 using an acoustic impulse (hand clap) while listening to the  
 94 result. This impulse could be enhanced in amplitude by  
 95 organizing the whole group to clap in unison together, per-  
 96 haps after a count of three. It would be worth noting that  
 97 many singers, speakers, and musicians, use a hand clap  
 98 acoustic impulse to test the acoustics of spaces to determine  
 99 optimum performance positions and these are not always  
 100 centre stage or behind a speaker's lectern.<sup>1</sup>

101 For a group studying a foreign language, the effects of a  
 102 poor signal-to-noise ratio due to competing sounds can be  
 103 made even more pronounced if the exercise is carried out  
 104 using message in a foreign language. If in addition the listen-  
 105 ers are not primed to expect a foreign language, the impor-  
 106 tance of having a robust method for verification becomes  
 107 apparent along with the overall quality of the spoken mes-  
 108 sage itself in terms of good diction and steady pace.

109 Use has been made of French and Latin phrases in this  
 110 way in a local school where short sentences were composed  
 111 by one of their teachers to ensure that they only made use of  
 112 vocabulary and grammar that would be familiar to the pupils.  
 113 Compared with using English, the background noise rose  
 114 much more rapidly and multiple attempts were required  
 115 before the listeners received even a meaningful message. Af-  
 116 ter swapping the speakers and listeners, the group was brought  
 117 together with the teacher who wrote the sentences and each  
 118 participant was asked to read out the message they received as  
 119 a listener and to offer a translation. Confirmation of the sen-  
 120 tence was sought from the speaker and the teacher often inter-  
 121 vened during the translation! Typically, the heard versions  
 122 were incomplete sentences; indeed on one occasion, a trans-  
 123 mitted Latin sentence was received as a French one! Here are  
 124 some example sentences and their translations in brackets.

- 126 (1) "Salve nauta!" agricola dicit. (*"Hello sailor!" said the*  
 127 *farmer.*)
- 129 (2) Mon grandpère a un nez énorme. (*My grandfather has*  
 130 *an enormous nose.*)
- 132 (3) Iuppiter est rex deorum. (*Juppiter is king of the gods.*)
- 133 (4) Mon chien est plus grand que ton hamster. (*My dog is*  
 135 *bigger than your hamster.*)
- 136 (5) Elefantus maximus in atrio sedebat. (*The most enor-*  
 138 *mous elephant was sitting in the hall.*)
- 139 (6) Mon chat préfère les gateaux au chocolat. (*My cat pre-*  
 141 *fers chocolate cakes.*)

142 **B. Wave shape transmission and integrity of data**

143 The integrity of data during transmission can be  
 144 explored using visually clear wave shapes and a large group  
 145 of participants standing or sitting in lines of any length, one

behind the other. All that is required in terms of apparatus is  
 a supply of paper and pencils. This exercise explores wave  
 shape degradation, where a given single cycle of a wave  
 form such as those shown in Fig. 1 are transmitted using  
 physical gestures down a line of participants.

The explanation to the group as a whole is that some  
 point, the person behind you will place their hands on your  
 shoulders and move your shoulders backwards and forwards  
 to represent the wave shape. They will take their hands away  
 to indicate the end and then you will be expected to repeat  
 this action on the shoulders of the person in front of you. A  
 demonstration should be given initially in front of everyone  
 to show how the movement relates to one of the original  
 drawn wave shapes; a push forward represents a positive  
 change (upwards on Fig. 1) and a pull back represents a neg-  
 ative change (downwards on Fig. 1). The person at the front  
 of each line is given a blank sheet of paper and a pen or pen-  
 cil with which to sketch the received wave shape from their  
 line. The exercise begins by giving the participants at the  
 back of each line a wave shape picture (see Fig. 1) and they  
 start its transmission down the line.

When all the lines have finished and the person at the  
 front of each line has a drawn version of the transmitted  
 wave shape, the first and last person from each line is invited  
 in turn to show the whole group the starting and ending wave  
 shape. Typically there will be significant differences between  
 these shapes and comparisons can be highly entertaining.  
 When the results from all the rows have been exhibited a dis-  
 cussion can follow that describes sound transmission through  
 air as longitudinal waves and how each person in a line was  
 in effect a molecule passing on the wave shape to the next  
 molecule. In addition, the types of differences found during  
 the exercise between the wave shape that was sent and the  
 one that was received can be explored in terms of the ways in  
 which errors in data transmission can occur such as missed  
 data, clipping, gain variation, and filtering.

**C. Sound levels**

An appreciation of sound levels and the decibel can be  
 provided if one or more sound pressure level (SPL) meters  
 are available (it is worth noting that SPL meter *Apps* are  
 available for mobile devices). The SPL meters should be  
 used with *A* weighting, approximating to the frequency

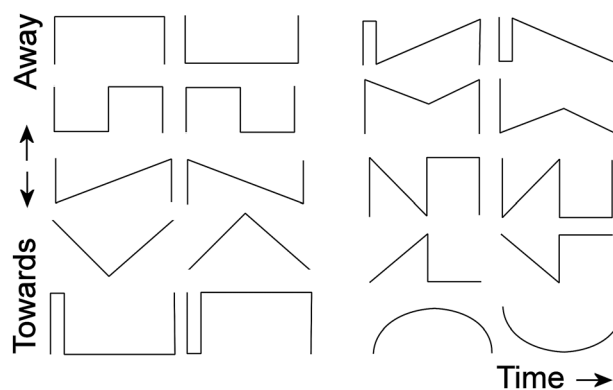


FIG. 1. Example wave shapes that can be used in the data transmission demonstration.

188 response of the human ear. Some means of measuring distance  
189 distance is also required as well as a large open space such as a  
190 school hall. SPL meter calibration should be demonstrated if  
191 a calibrator is available as this makes and reinforces the  
192 point that a dB SPL measurement is made relative to a refer-  
193 ence pressure value (in this case 20  $\mu$ Pa).

194 Two practical aspects relating to sound pressure level  
195 can be demonstrated as follows: (1) The change in dB when  
196 the sound pressure level of a source is doubled and (2) the  
197 dynamic range and comfortable playing level of musical  
198 instruments.

### 199 1. Change in dB for doubling sound source level

200 This experiment involves the use of an SPL meter and a  
201 sound source that can be doubled in pressure, consisting of  
202 spoken output from 1, 2, 4, 8, 16, and, if available, 32 mem-  
203 bers of the group. Some thought needs to go into the distance  
204 because the distance between the sound source and the SPL  
205 meter should be less than the critical distance (the distance  
206 from the source at which the direct sound and the reverberant  
207 sound are equal)<sup>2</sup> but not too low because the source itself  
208 will become considerably larger as more members are added  
209 to it. The critical distance can be estimated using Eq. (1)  
210 which requires the volume of the room and the reverberation  
211 time. Whilst both can be calculated, the reverberation time  
212 calculation requires information about the acoustic absorp-  
213 tion properties of the various surfaces in the room,<sup>2</sup> so in  
214 practice a value of 0.75 s could be used to allow a very ap-  
215 proximate working estimate of critical distance to be calcu-  
216 lated from the purpose of these demonstrations:

$$D = 0.057 \times \sqrt{\frac{V}{RT_{60}}}, \quad (1)$$

217 where  $D$  = critical distance (m),  $V$  = room volume ( $\text{m}^3$ ),  
218  $RT_{60}$  = reverberation time (s).

219 If two or more SPL meters are available then they could  
220 be placed at different distances; indeed, one could be placed  
221 beyond the critical distance to demonstrate the constancy in  
222 the level of the reverberant sound. Averaged multiple read-  
223 ings for each individual SPL meter could be taken for each  
224 sound source.

225 The sound source consists of the speakers each saying a  
226 different word repeatedly, such as “rhubarb, rhubarb,  
227 rhubarb,...”, and the SPL level is measured. To double the  
228 sound pressure level a second person is added and two of  
229 them each speak a different word each at about the same  
230 level while another SPL measurement is taken. Then the pro-  
231 cess is repeated for 4, 8, 16, and, if the group is large enough,  
232 32 speakers. One issue with this experiment is that the sound  
233 source should ideally be a point source so the mouths of the  
234 speakers need to be close together. Clearly this is not really  
235 very easy for a group size above about four, but in practice,  
236 the demonstration works well if the speaker group are very  
237 close together.

238 Following the measurements, the group can be given the  
239 values from one of the SPL meters that is within the critical  
240 distance for each sound source group (1, 2, 4, 8, 16,...) from

241 which they should work out the average change in dB for a  
242 doubling in sound pressure level. At a previously run ses-  
243 sion, the overall average change in dB per doubling was  
244 5.7 dB. Theoretically it should be  $\sim 6$  dB or  $20 \log_{10}(2)$ .

245 If SPL measurements were made beyond the critical dis-  
246 tance, then these should be seen not to vary particularly, pro-  
247 viding a basis for describing the nature of reverberation, the  
248 importance of the direct sound and why being within the crit-  
249 ical distance improves speech intelligibility and perceived  
250 clarity particularly of rapid music.

### 251 2. Dynamic range and comfortable playing level 252 of acoustic musical instruments

253 This demonstration requires at least one SPL meter and  
254 that at least some members of the group have their acoustic  
255 musical instruments with them. The object of the exercise is  
256 to find which player and instrument has the largest dynamic  
257 range measured in dB between the softest and loudest note  
258 they can play. An SPL meter (A weighting, set to an appropri-  
259 ate range, maximum capture if available) is used to measure  
260 the levels and it is placed at a fixed distance (1 m has been  
261 used but any distance within the critical distance that is not  
262 too close to the instrument is appropriate, providing it remains  
263 constant for all the measurements on a given instrument). If  
264 additional SPL meters are available these could be used at dif-  
265 ferent distances as discussed in Eq. (1) above. The player is  
266 instructed to sustain any note at the softest and loudest level  
267 they can achieve and also at a comfortable playing level. In  
268 each case, an SPL measurement is made. Average measure-  
269 ments could be taken for multiple attempts as desired.

270 The measured comfortable playing levels enable the rel-  
271 ative levels of the instruments to be compared, and this will  
272 provide a basis for a discussion as to why, for example, there  
273 are many more stringed as opposed to wind instruments in  
274 an orchestra. The dynamic range for each player and instru-  
275 ment is found in dB by subtracting the dB reading for the  
276 softest note from that for the loudest note. The results might  
277 be discussed in terms of the number of dynamic steps that  
278 are typically found in musical scores (e.g., *pp*, *p*, *mp*, *mf*, *f*,  
279 *ff*) and the fact that 1 dB is approximately the minimum  
280 change in level that humans can hear.<sup>2</sup>

### 281 D. Vocal fold vibrations challenge

282 The use of computers in singing training to provide real-  
283 time visual feedback of acoustic and voice source parameters  
284 has proved to be successful and is on-going.<sup>3-5</sup> During  
285 speech and singing related UK National Science and Engi-  
286 neering Weeks events for the public, the WINSINGAD<sup>6</sup> software  
287 was adapted to enable a display of the total number of vocal  
288 fold closures to be displayed in a large font on the screen of  
289 a laptop PC. The most accurate approach is to carry out the  
290 fundamental frequency ( $f_0$ ) analysis in the time domain<sup>7</sup> as  
291 each cycle can be accounted for directly. However, for the  
292 purposes of this challenge a good estimate can be made  
293 based on any microphone-based  $f_0$  analysis technique.

294 A vocal challenge that has been employed is to produce  
295 as many vocal fold closures as possible in one breath. While  
296 the  $f_0$  data is being gathered, the total number of cycles is

TABLE I. Top three results for the maximum number of vocal fold closures in one breath at the National Science and Engineering Week in York, UK in 2007.

Thursday	Friday	Saturday (adults)	Saturday (children)
Holly 7757	James 9920	Colin 20612	Joey 9030
Jack 7732	Alex 8397	Martin 18516	Ellery 8638
Eleonora 7169	Paul 8299	Jane 14896	Carriann 8472

297 shown on screen using a large font. To achieve a large num- 344  
 298 ber of vocal fold closures in one breath, two strategies will 345  
 299 help: (1) singing on a high pitch and (2) reducing breath 346  
 300 usage by singing quietly. Table I shows the top three results 347  
 301 for each of three days at the National Science and Engineer- 348  
 302 ing Week in York, UK in 2007. For this event the first two 349  
 303 days were devoted to local schools and the Saturday was for 350  
 304 members of the public, hence the entries for adults and chil- 351  
 305 dren on the Saturday. It turned out that Colin, who gained 352  
 306 the overall maximum of 20612 cycles in one breath, 353  
 307 achieved this due to his background as a trained diver!

308 **E. Efficient acoustic transmission**

309 The main topic for this exercise is amplification and it is 354  
 310 first introduced acoustically leading on to work on electronic 355  
 311 amplification and the use of a potentiometer. The acoustic 356  
 312 demonstration requires “talking tapes” (internet search for 357  
 313 “talking tapes” will find them) which have pre-recorded 358  
 314 messages on them in the form of a series of a number of 359  
 315 ridges across the tape which are the sound pressure varia- 360  
 316 tions from the originally recorded sound source. The tape is 361  
 317 played by holding it at one end securely with one hand 362  
 318 securely while running the thumbnail of the other hand along 363  
 319 the ridged side of the tape. A supply of plastic cups and/or 364  
 320 inflated balloons is also required. 365

321 When the tape is used on its own, the sound produced is 366  
 322 usually inaudible and some means of enhancing the energy 367  
 323 transmission from the tape to air is required. This can be 368  
 324 achieved by placing an object with a large surface area, such 369  
 325 as a plastic cup or an inflated balloon, against the held end of 370  
 326 the tape to enable the vibrations to be transmitted into the 371  
 327 room at a large enough amplitude to be heard by a small 372  
 328 group. 373

329 Talking tapes enable other aspects of sound to be dem- 374  
 330 onstrated. Playing the tape in the other direction time 375  
 331 reverses the message. Changing the playing speed varies the 376  
 332 pitch and overall timing. It is worth noting the effect of play- 377  
 333 ing the tape very slowly and very fast. These differences 378  
 334 could lead on to some thoughts about recorded sounds and 379  
 335 how they might be processed to make such effects. Analog 380  
 336 tape could be described (and possibly demonstrated if equip- 381  
 337 ment is available) as working in much the same manner 382  
 338 when it is reversed or played at different speeds. These 383  
 339 effects can be readily demonstrated digitally with shareware 384  
 340 audio wave editing software such as GOLDWAVE.<sup>8</sup> 385

341 **F. Speech and singing production**

342 This demonstration aims to provide an increased under- 386  
 343 standing of human speech and singing production and it can 387

348 makes use of acoustic models and demonstrations based on 349  
 350 the notion of the following:<sup>1</sup> power source (lungs and breath- 351  
 352 ing), sound source (vibrating vocal folds in the larynx for 353  
 354 pitched sounds such as the vowels, air being forced through 355  
 356 a narrow constriction for voiceless sounds such as the conso- 357  
 358 nants in “sea,” “she,” and “fee,” or a mixture of both for 359  
 360 sounds such as the consonants in “zoo,” “edge,” and “vee”), 361  
 361 and sound modifiers (the pharynx, oral, and nasal cavities 362  
 362 that make up the vocal tract). 363

364 A lung model has been used in acoustics education but 365  
 365 it is not available commercially<sup>9</sup> and would not be easy to 366  
 366 reproduce. An excellent resource that is available for demon- 367  
 367 strating the acoustics of speech production is the VTM-10 368  
 368 kit,<sup>10</sup> which comprises practical demonstrations of both the 369  
 369 sound source and sound modifiers during speech production. 370  
 370 There are two sound sources provided: (1) a battery-powered 371  
 371 electro-larynx that provides a falling f<sub>0</sub> over about 3 s and 372  
 372 (2) a whistle- type artificial larynx consisting of a small rub- 373  
 373 ber membrane that vibrates over a tiny hole when one blows 374  
 374 into its mouthpiece. Arai<sup>10</sup> notes that the use of prosthetic ar- 375  
 375 tificial larynxes has the following advantages: (1) their out- 376  
 376 puts are designed as a practical speech sound source, (2) 377  
 377 they are portable, and (3) sound source acoustic leakage is 378  
 378 low as their output signals are appropriately coupled to the 379  
 379 sound modifier tubes. 380

381 The VTM-10 kit sound modifiers are provided in two 381  
 382 forms. There are five acrylic tubes representing in cylindrical 382  
 382 cross-section the oral tract for the vowels /i/, /e/, /a/, /o/, and 383  
 383 /u/. In addition, there is a set of acrylic squares with central 384  
 384 holes of various diameters and these can be placed together 385  
 385 on a special frame to enable other vocal tract shapes to be 386  
 386 made up. In both cases, either of the two sound sources can 387  
 387 be used via a hard rubber coupler. Arai<sup>10</sup> also proposes the 388  
 388 use of a horn loudspeaker driver unit and he provides a 389  
 389 description of a suitable design for a hard rubber coupler, so 390  
 390 that it can be used as an electrical driver to enable any signal 391  
 391 to be used as excitation such as a pulse train, white noise or 392  
 392 the L/F source model<sup>11</sup> that is commonly found in practical 393  
 393 electronic synthesis systems such as the Klatt synthesizer.<sup>12</sup> 394  
 394 Three oral tract tubes and the sound sources from the VMT- 395  
 395 10 kit are shown in the upper left panel of Fig. 2. 396

396 The lower left panel of Fig. 2 shows a simple but effec- 397  
 397 tive power source and sound source model can be fashioned 398  
 398 out of the top section of a two liter plastic drinks bottle, three 399  
 399 plastic sandwich bags (marked “B” in the figure), plastic 400  
 400 insulating tape, plastic tubing with a “T” piece and a whistle- 401  
 401 type artificial larynx from the VTM-10 kit (marked with a 402  
 402 “W” in the figure). The T piece is fitted to one end of the 403  
 403 plastic tube and a plastic sandwich bag (B) is taped on each 404  
 404 of the two branches of the T as the “lungs.” The other end of 405  
 405 the plastic tube is taken through a hole in the screw-top lid of 406  
 406 the bottle, the lungs are emptied and the whistle-type artificial 407  
 407 larynx (W) is attached. The third plastic bag (B) is taped 408  
 408 around the bottom of the bottle as the “diaphragm.” The dem- 409  
 409 onstration is set up by unscrewing the top a little and pushing 410  
 410 the diaphragm into the bottom of the bottle tightening the top 411  
 411 to set the “raised diaphragm” position (to go with the “empty 412  
 412 lungs”). Breathing in is achieved by gently grasping the

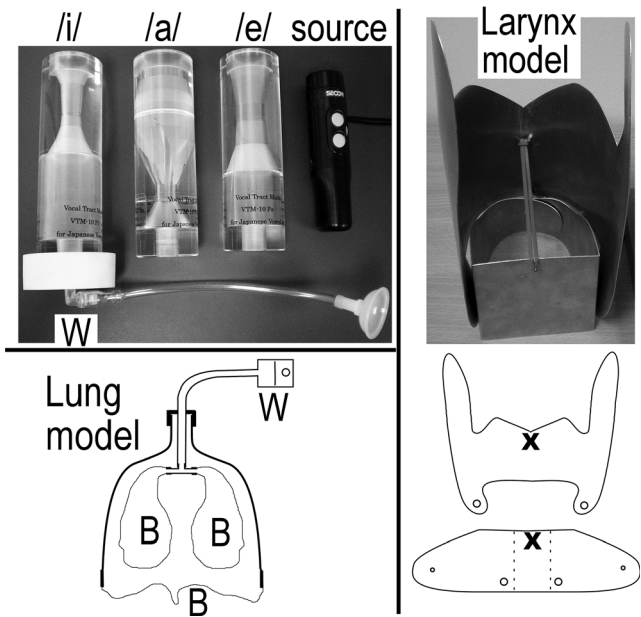


FIG. 2. VTM-10 acrylic oral tract tubes for /i/, /a/, and /e/ with whistle-type artificial larynx (W) and electrolarynx source (upper left); plastic bottle and three sandwich bag (B) lung model with whistle-type artificial larynx (W) (upper left); and aluminium larynx model supporting a rubber band with construction diagram (right).

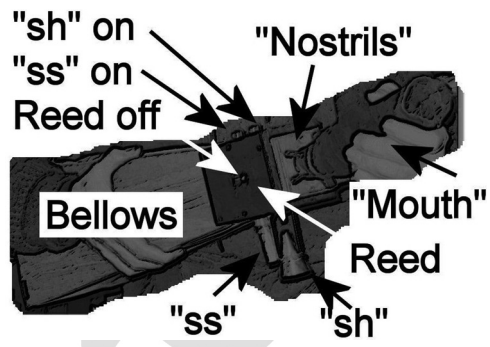
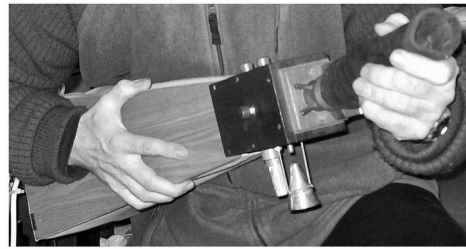


FIG. 3. Replica von Kempelin machine (Ref. 14) by Principal Pipe Organs of York, UK in its "playing" position (upper) and a summary of the controls for the instrument in this "playing" position (lower). The bellows provide the power source, an organ reed (tuned to Bb 2 around 120 Hz) provides the sound source and the leather tube marked "mouth" that is shown being "played" with the left hand provides the sound modifiers. The reed can be turned off and the "sh" or "s whistles" can be turned on by means of the buttons shown.

403 centre of the diaphragm and pulling it gently away from the  
 404 bottle. The lungs should inflate. On breathing out by pushing  
 405 the diaphragm into the bottom of the bottle, a sound is heard  
 406 from the whistle-type artificial larynx.

407 An on-line design for a tilting paper larynx<sup>13</sup> has been  
 408 modified to create an aluminium larynx that is around 25 cm  
 409 tall onto which rubber bands can be fixed to show how the  
 410 vocal folds are stretched as the larynx is tilted as illustrated  
 411 in the right hand panel of Fig. 2. It is fashioned from two  
 412 parts as illustrated in the figure that are bent appropriately  
 413 and joined at the points marked with "o" and "O." The ends  
 414 of the rubber band are attached to the points marked "X." It  
 415 should, however, be made clear to audiences that the laryngeal  
 416 voice source consists of two folds of muscle tissue  
 417 rather than two cord- or string-like structures and this can be  
 418 clearly illustrated if medical models of the larynx are avail-  
 419 able. Medical models of the lungs, bronchi, vocal tract, and  
 420 cut-away details of the head can also be used to enhance  
 421 understanding of human speech and singing production in a  
 422 graphical and hands-on manner.

423 A very visual demonstration of human speech produc-  
 424 tion can be made with a von Kempelen speaking machine<sup>14</sup>  
 425 of 1793, and for this a replica was commissioned from a  
 426 local pipe organ builder: Principal Pipe Organs of York, UK  
 427 which is shown in Fig. 3. The von Kempelen machine is use-  
 428 ful for demonstrating the basis of speech production because  
 429 it makes very visual and practical a model of the power  
 430 source, sound source and sound modifiers whilst having con-  
 431 siderable historical interest.

432 Since it is such an unusual object in itself, it provides an  
 433 excellent starting point for any workshop or presentation.

434 The physiology and acoustics of speech production can  
 435 be readily demonstrated in terms of the power source, sound  
 436 source, and sound modifiers.

1. Power source 437

438 The power source for speech and singing production is 438  
 439 the breathing mechanism for which two main muscle groups 439  
 440 are employed: (1) the diaphragm and abdominal muscles and 440  
 441 (2) the intercostal muscles of the lower ribs.<sup>1</sup> To breathe in 441  
 442 the thoracic cavity is enlarged which enlarges the lungs 442  
 443 thereby lowering lung pressure, and if the airway is open, air 443  
 444 will enter the lungs. To breathe out the thoracic cavity is 444  
 445 shrunk, the lung volume becomes smaller, lung pressure is 445  
 446 raised and air is expelled if the airway is open. The plastic 446  
 447 bottle lung model enables diaphragmatic breathing to be 447  
 448 demonstrated. 448

449 The importance of controlled breath control can be dis- 449  
 450 cussed in the context of singing,<sup>15</sup> where the key is to keep 450  
 451 the upper chest, shoulders and neck relaxed and free from 451  
 452 tension through the use of the two main muscle groups. The 452  
 453 first of these breathing mechanisms can be demonstrated by 453  
 454 placing a hand over the navel and breathing in trying to push 454  
 455 that hand outwards. The second can be demonstrated by 455  
 456 placed hands on the lower rib and breathing in while trying 456  
 457 to push outwards against the hands. During both demonstra- 457  
 458 tions, breathing in should be carried out without raising the 458  
 459 shoulders. 459

2. Sound source 460

461 The key aspect of the sound source is that it is a buzz- 461  
 462 like sound that changes in pitch but it remains buzz-like no 462  
 463 matter what sound is being articulated. An electrolarynx or 463  
 464 whistle-type artificial larynx allows this to be clearly demon- 464  
 465 strated since the buzz-like quality can be readily heard from 465

466 the device alone. When it is placed to one side of the Adam's  
 467 Apple against the thyroid cartilage with a closed glottis (by  
 468 holding one's breath) and activated, speech sounds are heard  
 469 as they are articulated. The tilting aluminium larynx model  
 470 enables the pitch changing mechanism to be demonstrated in  
 471 terms of how the vocal folds can be stretched.

### 472 3. Sound modifiers

473 The size of the sound modifiers is usefully shown with a  
 474 rubber tube, particularly if it has an appropriate bend in it (a  
 475 quest for something suitable was successful in finding a tube  
 476 from a Toyota 4 × 4 gearbox oil heat exchanger). Magnetic  
 477 resonance images of the vocal tract when articulating differ-  
 478 ent vowels show the differences in shape along the length of  
 479 the oral tract length and their shapes can be compared with  
 480 what is experienced during vowel production. The acrylic  
 481 tubes enable the shapes to be explored and the resulting  
 482 sound can be heard when an electrolarynx input is activated.  
 483 The (ex-Toyota) rubber tube can be placed over a suitably  
 484 sized loudspeaker that is driven by an electronic oscillator  
 485 and squeezed in different places to demonstrate vowel-like  
 486 sound modification.

### 487 4. Overall

488 For all demonstrations that involve a sound output it  
 489 might be appropriate to view the differences between the  
 490 sounds either as a waveform or a spectrum or a spectrogram  
 491 depending on the audience and purpose of the demonstra-  
 492 tion. If speech or singing formant synthesis is an appropriate  
 493 demonstration, then the MADDE freeware formant synthesizer  
 494 is an excellent demonstrator and it can be used in conjunc-  
 495 tion with RTSECT to show its acoustic output.<sup>16</sup> Whenever a  
 496 waveform and a spectrum or spectrogram are being dis-  
 497 played it is useful to indicate that the waveform is the signal  
 498 reaching the ear and the spectral representation is to a rea-  
 499 sonable approximation what is sent to the brain by each ear.  
 500 It is appropriate, though, to acknowledge that the linear fre-  
 501 quency axis should really be closer to logarithmic<sup>17</sup> and the  
 502 filter bandwidths should vary with center frequency<sup>18</sup> for  
 503 audiences who can readily appreciate these distinctions.

504 An example of the application of knowledge of speech  
 505 and singing production is in the creation of the singing of a  
 506 castrato by electronic morphing<sup>19</sup> which was carried out for  
 507 a BBC4 television program. Additional material written for  
 508 boys relating to their voice change in adolescence is avail-  
 509 able as a web resource set up to encourage boys to sing.<sup>20</sup>

### 510 G. Acoustic harmonic synthesis and organs

511 Harmonic synthesis can be readily demonstrated on a  
 512 computer using a freeware resource such as Pure Data  
 513 (PD),<sup>21</sup> or with a purpose-implemented iPad Application  
 514 such as "Harmonic Synthesis."<sup>22</sup> However, the use of organ  
 515 pipes makes for a much more physical and tangible acoustic  
 516 demonstration. The stops on an organ enable the player to  
 517 create different sounds through acoustic harmonic synthesis.  
 518 Most organ stops have a footage associated with them that  
 519 indicates the length of the open pipe that produces the lowest

note on the organ keyboard (two octaves below middle C). A  
 stop with an 8 on it indicates that the pipe for the lowest note  
 is approximately 8 ft long. Such a stop sounds at concert  
 pitch; in other words, the notes sound at the same pitch as  
 the piano.

Figure 4 shows a pipe organ demonstrator for a single  
 note that has 16 stops with one pipe for each stop built by  
 Principal Pipe Organs of York, UK, but a visit to a local pipe  
 organ will facilitate similar demonstrations. The demonstra-  
 tor organ is designed to show different types of organ pipes  
 as well as acoustic synthesis using harmonics 1 to 8. There  
 are two main types of organ pipe: flues and reeds. Figure 4  
 shows that the demonstrator has 13 flue pipes numbered 1 to  
 13 in the figure (harmonics 1–8 based essentially on princi-  
 pal pipes, harmonics 1–3 based on stopped flute pipes, and  
 two pipes that are slightly de-tuned to create a string  
 sound—salicional and voix celeste) and three reed pipes  
 numbered 14 to 16 in the figure (oboe, trumpet, and corn-  
 pean). The principal and string pipes are open and the flute  
 pipes are closed (the stoppers in their ends are visible in the  
 figure). Each pipe can be played separately or in any combi-  
 nation by means of small brass buttons and the unit has a  
 small electric blower to supply its wind.

The organ demonstrator enables acoustic harmonic syn-  
 thesis to be demonstrated through acoustic reinforcement of  
 individual harmonics as a practical demonstration of Fourier  
 synthesis. Harmonics are sine waves whose frequencies are  
 integer multiples of the fundamental frequency ( $f_0$ ) ( $1f_0$ ,  
 $2f_0$ ,  $3f_0$ ,  $4f_0$ ,  $5f_0$ , ...), and acoustically, they can be produced  
 using organ pipes of appropriate relative integer ratio  
 lengths. A pipe will have its  $f_0$  at the second harmonic of an  
 8 ft (concert pitch) pipe if it is half its length, or 4 ft ( $8/2$ ). A  
 pipe with its  $f_0$  at the third harmonic of an 8 ft pipe will be a

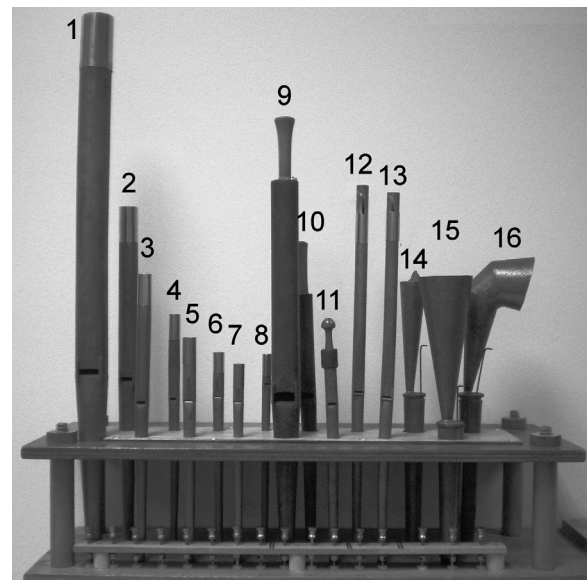


FIG. 4. Demonstrator pipe organ by Principal Pipe Organs of York, UK consisting of a pipe for one note (G4) of each of the following stops labeled numerically: (1) open diapason 8 ft, (2) principal 4 ft, (3) twelfth  $2\frac{2}{3}$  ft, (4) fifteenth 2 ft, (5) tierce  $1\frac{3}{5}$  ft, (6) larigot  $1\frac{1}{3}$  ft, (7) septième  $1\frac{1}{7}$  ft, (8) octavin 1 ft, (9) Hohl flute 8 ft, (10) block flute 4' ft, (11) piccolo 2 ft, (12) salicional 8 ft, (13) voix celestes 8 ft, (14) oboe 8 ft, (15) trumpet 8 ft, and (16) cornepan 8 ft.

TABLE II. Harmonic numbers, pipe length, number of notes from fundamental, musical interval and f0 for bottom C on an organ keyboard, or *manual*, for the first nine harmonics.

Harmonic number (n)	Stop name (principal)	Pipe length (8/n)	Notes from f0	Musical interval	f0 for C2 (bottom C) <sup>a</sup>
1	Open diapason	8	0	unison	65.41 Hz
2	Principal	4	8	octave	130.8 Hz
3	Twelfth	2 2/3	12	octave and a fifth	196.2 Hz
4	Fifteenth	2	15	two octaves	261.6 Hz
5	Tierce	1 3/5	17	two octaves and a major third	327.0 Hz
6	Larigot	1 1/3	19	two octaves and a fifth	392.5 Hz
7	Septième	1 7/8	21	two octaves and a flattened minor seventh	457.9 Hz
8	Octavin	1	22	three octaves	523.3 Hz

<sup>a</sup>2 octaves below middle C, 8 ft value in equal temperament relative to A4 (440 Hz).

third of its length, or 2 2/3 ft (8/3) and it will sound one octave and a fifth above concert pitch. Table II lists harmonic numbers, musical intervals and pipe lengths for the first eight members of the 8 ft harmonic series for manuals. A complete set of organ stop footages is provided in Ref. 3, p. 255, and on the “organ stops” iPhone application.<sup>22</sup> Discussion of pipe organs offers an excellent opportunity for working with fractions.

Harmonic synthesis for eight harmonics can be demonstrated acoustically and visually in terms of the lengths of the pipes themselves with the demonstrator. With a suitable spectrum or spectrographic display it can be shown how each of the harmonics added to the 8 ft has its own fundamental aligned with the appropriate harmonic of the 8 ft pipe.

The use of an organ demonstrator or a visit to a local pipe organ can provoke thinking and discussion as to how a pipe organ works, the number of pipes and their pitch range. This thinking could be supplemented by indicating that a large pipe organ can span an overall frequency range that is greater than that of human hearing and an overall dynamic range that is greater than any other musical instrument. In addition, a pipe organ is a complex and large feat of engineering, which is highlighted through a visit to a local organ to meet the organist and explore the instrument itself, perhaps using a laptop with a real-time spectrum or spectrogram display.

### III. ASSESSING THE SESSIONS

It is always important to know how successful or otherwise learning activities are in order to inform, for example, sponsors, parents and teachers, but effectiveness of such sessions is something that is not easily quantified, particularly

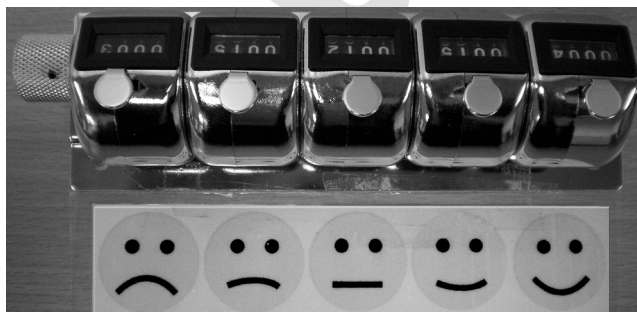


FIG. 5. Set of five tally counters with smiley faces.

with younger groups. There was an expectation that the effectiveness of sessions would be quantified during the Senior Media Fellowship, for which the following technique was developed.

The original thinking was based on the fact that some sessions would be run with young children and that time was always at a premium, and on this basis the use of questionnaires was ruled out. Awareness of the fascination that many of us and especially the young have for pressing buttons led to a multiple set of five stock-taking tally counters being purchased of a type that is used to enable different types of stock to be counted separately. Originally the idea was to ask questions with a choice of answers, but further thought provided the idea of associating the five tally counters with five smiley faces from happy to sad (see Fig. 4) which could be used to gain responses to “I feel confident about...” style statements.

The procedure adopted was to invite participants to respond to such a question by pressing the button next to the appropriate smiley face on entry to and again on exit from a session (Fig 5). The statements might be as follows but would vary depending on the audience and the activity itself:

- (1) “I feel confident describing how science works.”
- (2) “I could describe harmonic synthesis to others.”
- (3) “I know all about my voice.”
- (4) “I have learned something about my voice.”

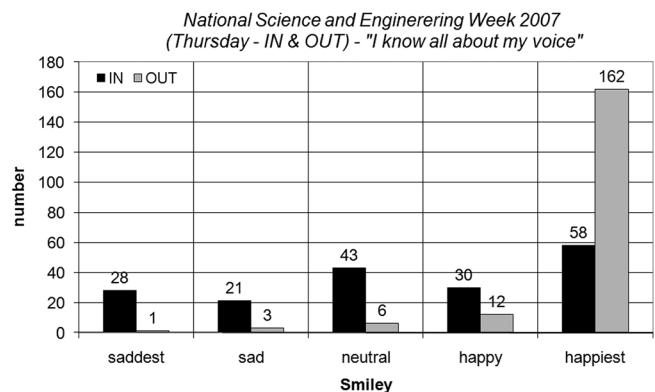


FIG. 6. Example data from the tally counters for participants (school pupils aged 9–16 years) on entry and exit to a voice production session at a Schools’ Day during National Science and Engineering Week 2007 in York UK in response to the statement “I know all about my voice.”

614 The results for entry are noted at some point during the  
615 session by copying down the five numbers, the tally counters  
616 are reset ready to be used on exit. Two sets of tally counter  
617 data result, one at the start and one at the end of a session.  
618 Figure 6 shows tally counter data for a National Science and  
619 Engineering Week event in 2007 at which human voice pro-  
620 duction was explored with 184 nine to sixteen year olds in  
621 which the differences between the two results are statisti-  
622 cally significant at the 0.1% level (Chi-sq, 4 degrees of free-  
623 dom: 64.48,  $p < 0.001$ ).

624 **IV. CONCLUSIONS**

625 Acoustic science is something of a mystery to many  
626 people possibly because it cannot be seen or easily interacted  
627 with. This paper has described a number of acoustic demon-  
628 strations that can be readily implemented, in some cases  
629 with everyday objects, and used both in schools and with the  
630 general public. Increasing public understanding of science is  
631 important in today’s society where scientific and technical  
632 advances play increasingly important roles in human exist-  
633 tence. Scientific engagement at an appropriate level can play  
634 a vital role in increasing public understanding and awareness  
635 of scientific principles and to make progress with such  
636 engagement, it does not matter what topic is used. In addi-  
637 tion, it can encourage young people to think about careers in  
638 related professions, such as engineering, information tech-  
639 nology, physics, chemistry, or mathematics. Assessing the  
640 effect of scientific engagement is not easy particularly with  
641 children, and an assessment technique based on single button  
642 presses on entry and exit from an event is described that has  
643 been used effectively with all age groups.

644 Acoustics offers a special vehicle for this process since  
645 the demonstrations can be heard and there is a heightened  
646 degree of fascination with topics that engage directly with  
647 the human senses. The principles behind acoustic harmonic  
648 synthesis, whether by organ pipes or electronic means,  
649 underpin major topics in physics and engineering. Young  
650 minds that are opened to these and other phenomena may  
651 well become tomorrow’s generation of scientists, technolo-  
652 gists, and engineers that society needs.

653 In seeking to engender a sense of awe, wonder, and  
654 amazement, acoustic demonstrations that engage with music,  
655 sound synthesis, speech and singing appeal powerfully to  
656 audiences; anyone can join in and hear the effects being con-  
657 sidered. Knowledge of how the body works, in this case the  
658 speech and singing production system with some reference  
659 to hearing, is of interest to most people since they all have  
660 something to gain directly out of increased knowledge in  
661 these areas. In addition, reference to healthy speech and  
662 singing production and hence healthy breathing and posture

as well as timely advice on noise induced hearing loss and  
looking after the hearing system as appropriate offers poten-  
tially long-lasting general health benefits.

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