Speech Intelligibility and Fire Alarm Systems

Results and Discussion from Commercial Venues

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Introduction

Messages broadcast over Emergency Voice Communication Systems (EVCS) can provide information to help occupants decide what actions to take for different event scenarios, such as fires, weather events, or terrorist attacks. It is imperative, therefore, that people receive content that is comprehensible. Such understanding can be influenced by the message itself, the talker and listener(s), the system by which the message is transmitted, and the acoustic characteristics of rooms and their contents. Given the need for real-time messages during certain events, the ability of fire protection engineers to ensure the quality of the message or its content is limited; thus, approval of such systems has focused on quantifying whether the EVCS can reproduce signals faithfully over the range of frequencies pertinent to speech and to what degree the building construction and system design (e.g., speaker number and locations) reduce the intelligibility of a message. Several studies [1-6] have evaluated the effects of additional or alternate speaker locations, floor and wall coverings, background noise, furnishings, and numbers of occupants in a variety of spaces on the measured signal, with particular focus given to spaces that might be found in commercial facilities. A separate evaluation of stairwells illustrates the difficulty in improving message comprehension in such spaces. This paper will identify some of the findings from those efforts.

Background

The intelligibility of an EVCS can be evaluated by subjective [7, 8] and objective [9, 10] methods. The former are variations of participant-based schemes, in which trained personnel listen to broadcast messages and record the word, words, or sentences that they hear; typically, the broadcast words or phrases are constrained to a list. The latter, objective tests, replace the human talkers and listeners with equipment. One component broadcasts a specially constructed, multi-frequency test signal over the EVCS; simultaneously, a meter measures the strength and comparative quality of the signal at different locations throughout the facility. [11] These meters [11, 12] use a variation of Speech Transmission Index (STI) measurements to evaluate the impact of changes to the EVCS and to the building environment. STI evaluates 98 combinations of modulated noise, using 14 modulation frequencies and 7 octave bands, to provide a single number that represents the impulse response and signal-to-noise ratio for a given area, accounting for noise, reverberation, echoes, non-linear distortion, and band-pass limitations of the system and environment. [13, 14] A reduced set of two modulation frequencies and six octave bands (STI-PA) is used in handheld meters and results in a difference from the complete STI analysis of ±0.03. [12] The results of the various test methods can be compared against the Common Intelligibility Scale (CIS). [13]

A CIS of 0.7 [9] or 0.70 [15] has been selected as the breakpoint for intelligibility of emergency systems; this corresponds to comprehension of approximately 80% of words and 95% of sentences. An equal or higher CIS indicates that people within that room should be able to hear and understand a message broadcast over the EVCS, while a lower score indicates that people may have trouble hearing the message (at least in certain areas of the room) or may be unable to understand enough of the words to comprehend the message. For people with a hearing disorder or in locations where very complex messages are used, a higher CIS may be required.

The meters require about fifteen seconds per measurement. Current recommended practice [11] suggests a minimum of one measurement location for every 37 m^2 (400 ft^2) with two measurements at each location; if the two CIS readings are not within 0.03 of each other, an additional reading should be taken, and the average of the two closest measurements is recorded for that location. The analyzer microphone should be maintained at least 0.6 m (2 ft) from the user and approximately 1.5 m (5 ft) from the floor, although some measurements might be collected at a height representative of a seated individual, if appropriate.

Test Facilities

The results of studies from four types of spaces commonly found in commercial facilities are described below.

Cafeteria Dining Room

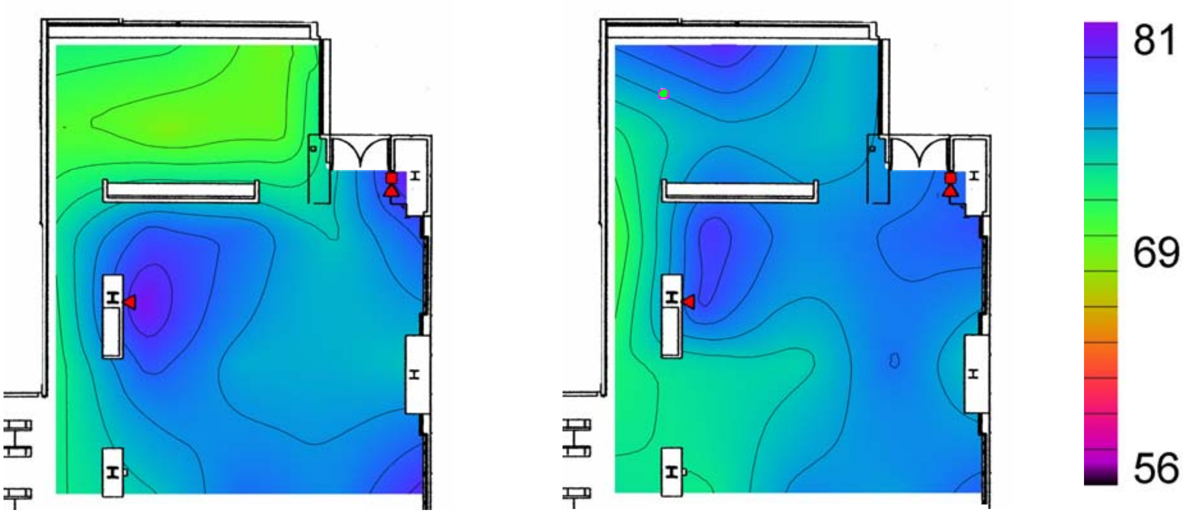
A dining room, composed of one large room with small alcoves to the north and south, is the first area to be considered. The main dining area is approximately 27 m (88') by 13.5 m (44'). Dining room alcoves at either end of the main area are 4.8 m (16') by 9.7 m (32') and are separated from the main dining room by 6.1-m-long (20') wood and plastic dividers that span from floor to ceiling. Wooden benches with cloth-covered foam cushions are located on the alcove side of each divider. The floor plan is nearly reflective about the east-west centerline, with the exception of a corridor entrance to the east-northeast. A more complete description of the facility is provided elsewhere. [1]

Four speakers had been installed in the main dining room, with two mounted on freestanding walls near the entrance from the cafeteria and two mounted near glass exit doors. During a second test series, a temporary, ceiling-mounted speaker was installed in the southern alcove for evaluation. Intelligibility was measured throughout the space, with 6 locations in the alcove and 15 in the main dining area (exclusive of measurements proximate to each of the pre-installed speakers). This represents approximately three times the suggested measurement density [11] of one location approximately every 37 m^2 (400 ft^2). The results for the two series are provided in Figure 1.

For the system as installed, the intelligibility measured for the two areas – main dining room and alcove – was 0.75 ± 0.02 and 0.67 ± 0.02 CIS, respectively. [3] If both spaces are considered a single room, the combined intelligibility, using all measurement locations, is 0.73 ± 0.04. This changes marginally (0.72 ± 0.04) if the number of locations is reduced to the suggested measurement density. [1] It may be of note that the highest intelligibility achieved in the space was 0.81 CIS, as measured 1 m (3') from each of the four speakers. Installing a speaker in the alcove improved the intelligibility in that space to 0.74 ± 0.03 (see Figure 1b).

Open-floor-plan Office Space

The second space to be considered is one that is fairly typical of many office buildings: an office space with an open floor plan (i.e., one with minimal walls). For these spaces, there is a



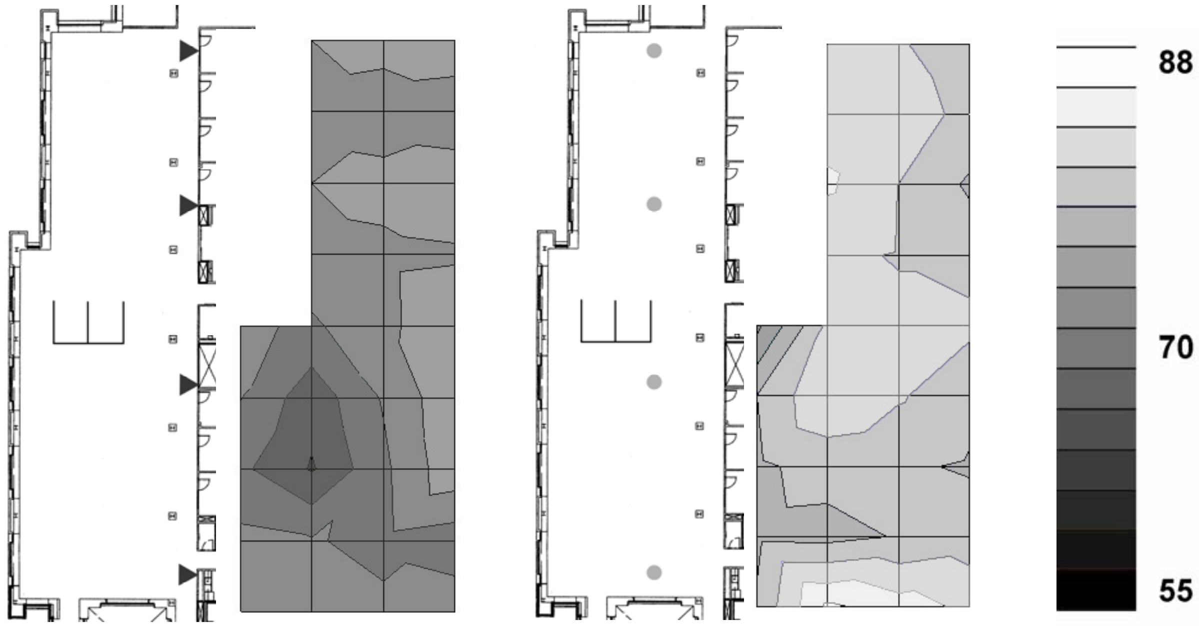
a) As installed b) Additional Speaker

Figure 1: Intelligibility measurements (shown in CIS*100) for the dining area of a cafeteria in a commercial building. a) shows the results for the system as installed, while b) illustrates the impact of an additional speaker. This dining area consists of a dining alcove (the small area in green at the top of a) and a main dining area. Only half of the entire space is shown.

central mechanical core – enclosing stairwells, bathrooms, elevators, mechanical rooms, and, in this building, offices and conference rooms – surrounded by a large, undivided area. The core runs nearly the length of the building with a 3.5-m-wide (11.5’) corridor at either end. Four cross corridors connect the open areas on either side of the core. The intelligibility of one of the open spaces was evaluated; this portion is composed of two rectangles (see Figure 2): one is 25 m (84’) in length and 13 m (42’) in width and the other is 16.4 m (54’) by 10.9 m (36’). A row of concrete columns, 7.6 m (25’) on center, is located 2.1 m (7’) from the outer wall of the core. The ceiling is 2.7 m (9’) above the floor. A more complete description of the facility is provided elsewhere. [1]

The original voice communication system for the space has four combination speaker/strobe devices installed approximately 2.1 m (7’) above the floor in the southern (core) wall. Four additional speakers were mounted on the ceiling, in line with the wall-mounted speakers and 5.4 m (18’) from the northern wall. These speakers were used to compare wall- to ceiling-mounted speakers in the space. Measurements for speech intelligibility were spaced 1.5 m (5 ft) apart in the longer direction. The three rows of measurements were 5.2 m (17’), 7 m (23.25 ft), and 11.2 m (37 ft) from the wall of the office area.

Results for intelligibility measurements of the existing EVCS are shown in Figure 2 for the two cases of wall- and ceiling-mounted speakers. Note that the same power taps and signal strengths were used in both cases and the speakers were from the same manufacturer and model family. For wall-mounted speakers, the average CIS for the room was 0.75 ± 0.03 [4]; although measurements of intelligibility exceeded 0.70 for the majority of the space, an area in the center of the room had two deficient locations, with the lowest averaging 0.67 CIS. Replacing wall- with ceiling-mounted speakers (Figure 2b), the average intelligibility improved to 0.83 ± 0.03; some locations recorded average measurements as high as 0.88 CIS and the island of poor intelligibility no longer exists.



a) Wall-mounted Speakers a) Ceiling-mounted Speakers

Figure 2: Intelligibility measurements for an office area with an open floor plan are shown. a) and b) provide plan views of the office space (left), including locations of speakers (triangles and circles, respectively), and a contour map of the CIS measurements (right) for wall- and ceiling-mounted speakers, respectively. The figure illustrates the improvement of intelligibility possible through relocation of speakers.

Large Conference Room/Classroom

A classroom was selected to evaluate the effect of a number of variables on speech intelligibility. The room is approximately 18 m (60') long by 7.1 m (24') wide and 2.9 m (9.5') high. Eight variables were considered for the study – speaker quantity and location, speaker power tap, sound pressure level (SPL), number and location of occupants, presence of furniture, location of intelligibility measurements, data collection method, and floor covering – in 99 experiments [5], although the results of only a few will be presented here.

Of the experiments, 31 were conducted with carpeted floor and a SPL of 78 dBA. The remaining tests were conducted at 61 dBA: 37 with carpeted floor and 31 with 1/8-inch flat tileboard, which had hardboard backing, over the carpet. All of the tests conducted at the higher SPL had room intelligibilities (average CIS of measurements in the room minus the standard deviation) in excess of 0.70. At the lower SPL, however, approximately 46% of the carpet and 58% of the tileboard experiments had room intelligibilities below 0.70. With all other variables constrained, room intelligibilities for experiments with carpet exceeded those for tileboard when the speakers were tapped at 1/8, ¼, or ½ watt. For 1-watt taps, the results were mixed; at 2 watts, the results were nearly identical. Room intelligibility either increased slightly (4/6 tests) or stayed the same with furnishings, consisting of metal-framed tables with Formica tops and rolling office chairs with metal frames and padded seats. See Ref. [5] for a complete discussion of the results for each variable.

One of the parameters examined was the effect of occupants – both number and location – on speech intelligibility measurements. A few tests for unoccupied rooms were repeated with ten

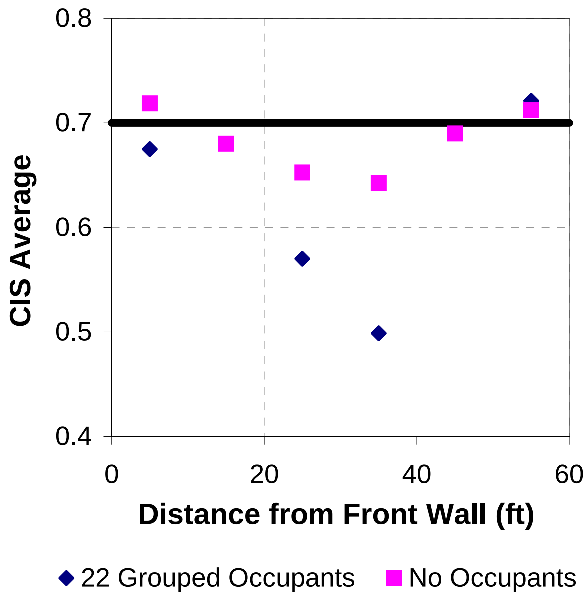


Figure 3: Intelligibility measurements in a classroom with and without occupants. The occupants were seated near the center of the room, and four speakers were sounding, one in each corner of the room. No measurements were taken 4.5 m (15') or 13.6 m (45') from the front wall

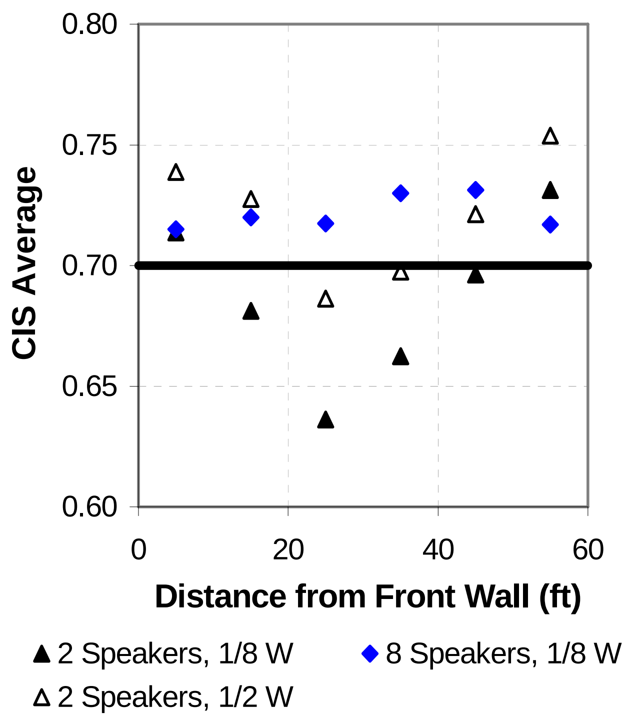


Figure 4: Intelligibility measurements in a classroom with different numbers of speakers sounding, showing the influence of measurement location and supplied energy on intelligibility

and twenty-two seated occupants, either grouped together near the center of the room or scattered throughout. While the differences, in general, were slight, the tests involving grouped occupants had consistently lower CIS measurements than those for scattered occupants or for unoccupied rooms. Measurements for one case, in particular, are provided in Figure 3 with comparative results from an unoccupied room. (Note that the number of locations for measurements was reduced for the occupied room owing to time constraints.) Twenty-two people were seated at tables, grouped, near the center of the room and tileboard covered the carpet. Four speakers, one in each corner of the room and tapped at 1/8 watt, were sounding. The averaged measurements near the occupants were significantly lower than those for the unoccupied room, by as much as 0.14 CIS, although measurements near the speakers were much closer.

Sixteen speakers – twelve mounted in the ceiling and two each on the front and back walls – were independently controlled to assess the impact of speaker number, location, and power on intelligibility measurements in the room. Figure 4 provides a graph of average CIS measurements as a function of location within the room for different numbers of speakers and for different power taps. In the case of two speakers installed on the ceiling at the front and rear of the room, the minimum measurement occurs directly between the speakers. (Note that each data point represents an average of measurements from two locations, with four readings from each location.) Increasing the power taps from 1/8 watt to ½ watt increased the intelligibility from 0.69 ± 0.04 to 0.72 ± 0.03, where the standard deviation is based on all 48 measurements. Changing from two, ½-

watt to eight, 1/8-watt speakers reduces the standard deviation (0.72 ± 0.02); furthermore, the profile is smoother and there are no individual measurements below 0.70 CIS as is the case with two speakers.

Stairwell

A separate series of tests was conducted in a four-level emergency stairwell to evaluate the influence of speaker number and power and SPL on intelligibility in such spaces. For this preliminary investigation, the stairwell was not occupied. Speakers were installed on every landing; for the base case, only those speakers on landings with doors were sounding and they were tapped at 1 watt. Measurement locations are shown in Figure 5 for the base case. The number of locations was reduced by about half for other scenarios.

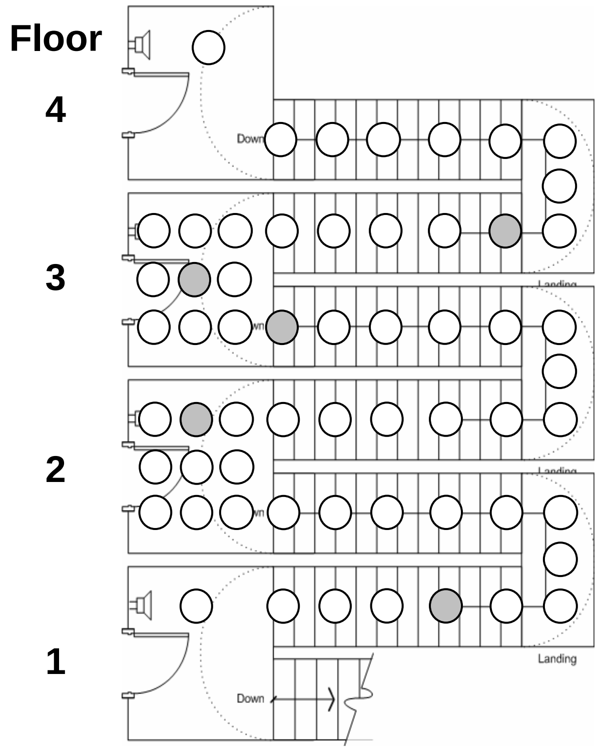


Figure 5: Stairwell intelligibility was measured at numerous locations (circles), with five to ten readings at most locations and 100 measurements taken at the shaded circles. The landings to the right are reversed for this representation.

The averages the first five measurements for all locations are provided for each experiment in Table 1. As can be seen, no variations to the test parameters resulted in average measurements above 0.65. The variations – changes to the power tap, SPL of the broadcast message, and inclusion of speakers on the alternate landings – provided no significant change. Individual measurements for the base case varied from 0.43 to 0.80 CIS, and average measurements (by location) from 0.52 to 0.76. Similar results were found for an EVCS installed in a stairwell in a separate test series. [1, 2]

As noted above, 100 measurements were taken for the base case at five locations in the stairwell to determine variation in measurements in this acoustically hard space. Statistics for the measurements are provided in Table 2. Locations 1 to 5 refer to the shaded circles in Figure

Table 1: Library Stairwell Data

Case	Avg	σ	Avg-σ
Base	0.65	0.04	0.61
¼ W	0.65	0.04	0.61
½ W	0.65	0.04	0.61
2 W	0.63	0.04	0.59
85 dBA	0.64	0.04	0.60
76 dBA	0.63	0.04	0.59
All Landings (1 W)	0.63	0.03	0.60
All Landings (½ W)	0.63	0.04	0.58

Table 2: 100-measurement Stairwell Data

	Location				
	1	**2**	**3**	**4**	**5**
Max	0.73	0.69	0.70	0.69	0.71
Min	0.58	0.61	0.47	0.61	0.59
Avg	0.66	0.65	0.63	0.65	0.63
Median	0.65	0.65	0.64	0.65	0.63
σ	0.024	0.015	0.038	0.016	0.019
Avg-σ	0.64	0.63	0.59	0.63	0.61

5, numbered from top to bottom. Variations in measurements at these locations are slightly less broad (0.47 to 0.73) than those for the entire space (0.43 to 0.80, as noted above). For each location, the average and median measurements are fairly close, and the distribution is approximately Gaussian, as shown in Figure 6.

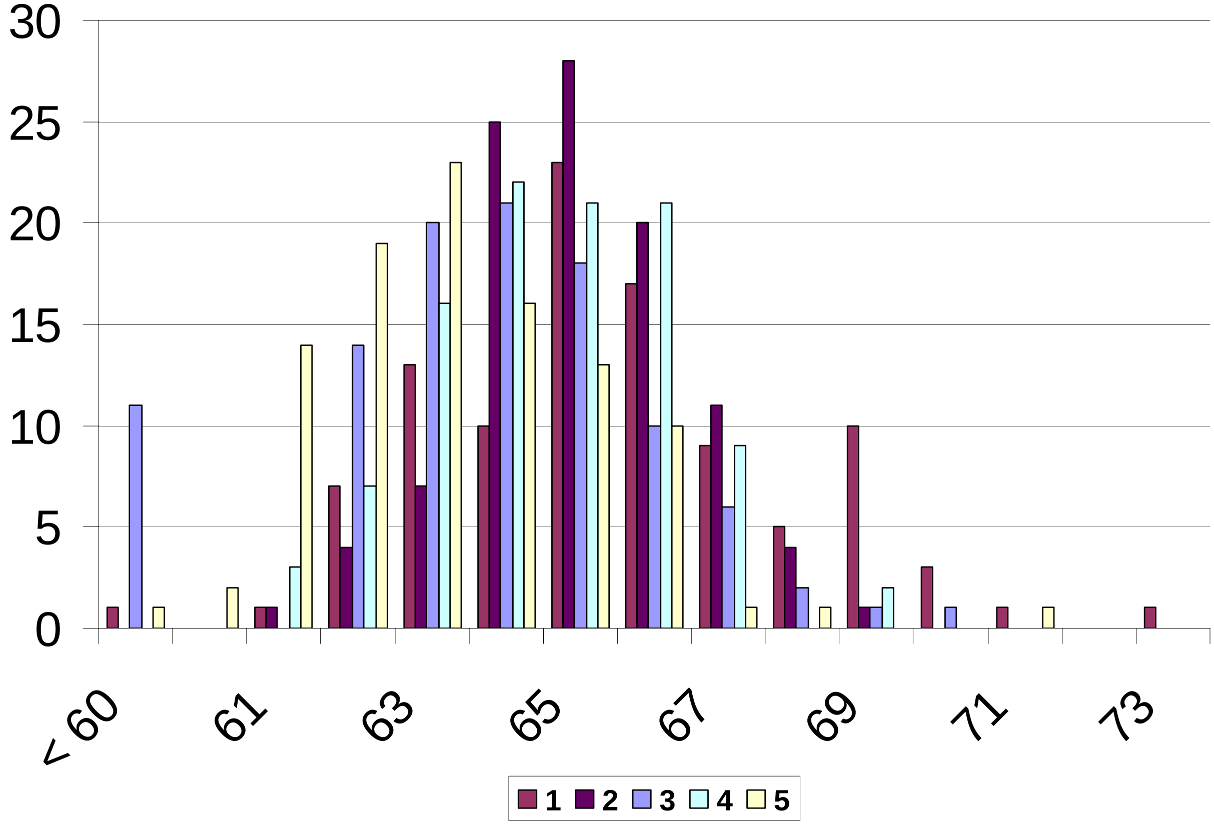


Figure 6: Histogram of measurements from stairwell. The abscissa is the CIS measurement, and the ordinate is the number of measurements within that range.

Conclusions

Speech intelligibility tests evaluate whether a message broadcast over an Emergency Voice Communication System (EVCS) could be heard and understood. This paper explores how different system design and environment conditions (e.g., furnishings) and, to a lesser degree, measurement techniques might influence the characterization of the intelligibility of a space. Four types of rooms are examined: a cafeteria dining area, a large office space, a classroom, and a stairwell.

The influence of speaker number and location is a consistent theme through all spaces, excepting the stairwell. Moving speakers from the wall to a more central location on the ceiling reduced variation and increased the overall intelligibility of the office space. A similar improvement was noted with the addition of a single speaker to the alcove of the dining area. For the classroom, increasing the number of speakers at a given power tap improved both the overall room average and the distribution of intelligibility. The average room intelligibility was very similar for the case of two and eight speakers at ½- and 1/8-watt taps, respectively – in which cases the total power provided to the room is equal – although the intelligibility profile was improved in the latter case. The distribution profile remained unchanged when the power tap was changed from 1/8 to ½ watts/speaker, although the values increased measurably.

Occupant loading had a marginal effect on overall room intelligibility in many cases, although the results were consistent for multiple scenarios. As might be expected, grouping the occupants reduced the intelligibility over an unoccupied space; this may influence the timing of intelligibility testing for fire protection purposes, given that such evaluations are typically conducted prior to occupancy, which may give misleading results.

Finally, two separate stairwell investigations have not identified an appropriate system design that would provide intelligibility throughout that space. This is somewhat problematic, given that the International Fire Code, at the least, identifies stairwells as one of the paging zones of interest in high-rise buildings. [16] A further complication arises when the inclusion of occupant loading to the stairwell is considered; this is an area in which more research is needed.

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