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VALIDATION OF TRRL LISTENING ROOMS FOR VEHICLE NOISE NUISANCE STUDIES

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1. INTRODUCTION

In the UK vehicle noise is controlled by Type Approval and Construction and Use regulations which specify the maximum noise levels, in dB(A), that vehicles can emit during a full throttle acceleration test. However there has been concern that some vehicles producing the same test sound level can differ appreciably in terms of subjective noisiness, indicating that the use of the maximum dB(A) may not always be appropriate in controlling noise nuisance. An experiment at TRRL was conducted in 1988 where juries were assembled to rate the noisiness of vehicles as they were driven past. Recordings of vehicle noise were taken and this enabled the relationship between various measures of noise and subjective noisiness to be quantified. It was concluded that, although maximum dB(A) was one of the best correlated measures, other measures based on loudness levels showed promise and should be examined further under more controlled conditions.

Listening room facilities have been developed at TRRL where greater control of pass-by noise is achieved by using a digital sound replay system. Exactly the same acoustic events can be presented to listeners thereby enabling greater statistical precision in establishing any differences between noise measures to be obtained.

A validation experiment has been designed to test the degree of realism achieved. In outline, recordings of vehicle pass-by noises made outside the building used in the jury experiment referred to above were replayed to a number of listeners. The ratings of this replayed noise made in the listening rooms designed to simulate indoor and outdoor listening conditions were then correlated with the ratings made by jury members in the original experiment. In the original experiment ratings of noisiness were made both outside and inside a specially constructed bungalow, so that the efficacy of various noise measures in predicting disturbance indoors and outdoors could be examined. Full details of the original study have been reported elsewhere [1,2].

This paper describes the listening room facilities that have been developed at TRRL and the results of the validation study.

2. DESCRIPTION OF THE LISTENING ROOMS

The rooms were designed to enable subjective assessments of vehicle noise nuisance under partially reverberant conditions corresponding to indoor listening conditions and under free-field conditions similar to those encountered outdoors.

VALIDATION OF TRRL LISTENING ROOMS

Listening room 1 (LR1) shown in Figure 1a has the dimensions of a typical living room (4.5m x 3.4m x 2.6m) and is furnished appropriately with fireplace and coal effect electric fire, settee, TV, bookcase and coffee table. Lighting is provided by a central ceiling light and a single wall light fixture. The floor is of a suspended wooden construction covered with a short-pile carpet. The suspended floor is similar to that found in many pre-war houses and allows acoustically coupled vibrations to be felt during the noisier events. A vibration nuisance survey [3] has shown that low frequency noise frequently produces this effect in houses located close to heavily trafficked roads. In one wall, 0.25 m thick, there is a flat glazed area with a single opening casement window. The glazed area of 1.7m x 1.2m is within the normal range of window sizes for this type of domestic room. On the far side of this glazed wall is a large room 15m long which houses the speaker for sound reproduction. The room is partially lined with sound absorbing tiles to reduce sound reflections which might create an unrealistic sound field. Curtains were drawn across the window so that the realistic indoor domestic conditions were not degraded by the view of the speaker and room beyond.

Measurements were made of the noise reduction afforded by the glazed wall to check whether it was similar to that found in actual domestic properties. For this purpose pink noise was reproduced and sound levels in each 1/3 octave band over the audio range were measured at two points 1m from the outside "facade" and at two points inside the room (at the geometric centre and at a height of 1.2m and ½m from the wall facing the window). The differences between the averaged levels inside and outside the room were plotted for each band frequency as shown in Figure 2. Survey data for a wide range of domestic front windows [4] has shown a similar trend, ie increasing attenuation at high frequencies and an attenuation between 20 and 35 dB in the range 100 Hz to 4KHz as can be seen in Figure 2. The large differences at low frequencies are due to room modes which are determined by room dimensions. Individual sites show similar effects but the variation is not apparent when site data is averaged. The partition in LR1 was therefore considered to attenuate noise in a similar way to actual house facades. This indicated that noise recorded outside and replayed through the speaker would have a realistic balance of high and low frequencies when measured inside this listening room.

The listeners in this room were seated close together along the wall facing the window area. The seating positions are indicated in Figure 1a. It should be noted that the TV was not switched on since it was considered important not to distract the listeners from their task of assesssing the vehicle sounds. Measurements using replayed pink noise showed that using three subjects in this location the differences between 1/3 octave noise levels at head positions were less than 10dB, the average difference being 3dB. Differences in maximum dB(A) and dB(C) levels were of the order of 1dB.

Listening Room 2 (LR2) is an anechoic chamber of overall dimensions 4.9m x 4.8m x 4.8m with glass fibre filled wedges on all surfaces (Figure 1b). Sufficient wedges were removed to allow space for the speaker and three listeners. The speaker was placed in one corner of the room and the listeners were seated close together in an arc near the centre of the floor space 2m from the speaker cone. As before, checks were made on the level differences in noise levels in each 1/3 octave band at each subject's head position. Differences were generally of the order of 1dB and the largest difference was 3.5 dB.

3. VALIDATION TESTS

3.1 Equipment

The original recordings and sound replay in the listening rooms were made using a digital audio tape deck. This had a dynamic range of over 90 dB which is very large compared with analogue tape recorders. This allows very loud and quiet sounds to be reproduced accurately without the electrical noise or distortion problems common with analogue systems. Because of deficiencies in the low frequency (ie <60 Hz) response of the speaker and the fact that the room dimensions and facade attenuation differed between LR1 and the room used by listeners in the original jury experiment it was necessary to make some adjustments to the levels of the reproduced sound. A good match between the band spectra obtained at the centre of the original jury position and the centre of the listening position in LR1 was obtained by making some adjustments to the lower 1/3 octave frequency bands (ie <1000Hz). Some adjustments were also necessary in LR2 in order to ensure similar levels to that measured in the middle of the original jury seated outside. The adjustments were made by connecting a digital equalizer between the tape recorder output and power amplifier input. This unit was programmable and it was possible to adjust each 1/3 octave level in the frequency range 40 Hz to 16 kHz by up to ± 16 dB and store the setting in a memory for future use.

For the purpose of determining settings, an 8s recording of a noisy
ehicle idling was replayed several times with different 1/3 octave weightings until close agreement was obtained between the reproduced levels at the centre subject's head position in the listening rooms and those levels measured at a similar height in the middle of the original juries inside and outside the bungalow.

Following equalization the signal was amplified using a power amplifier which delivered up to 90 watts into an 8 ohm load. The speakers employed were 80w, 8 ohm impedance with dual concentric cones and bass reflex ports. The largest cone diameter was 400 mm. Tests in the anechoic chamber showed a reasonably linear response above 60 Hz. They were capable of reproducing vehicle noise at sound levels in excess of 100 dB(A), on axis at 2m, under free-field measurement conditions.

3.2 Recordings

The recordings of 40 vehicle pass-by events taken at the facade of the bungalow in the original jury experiment were used in the validation experiment. A block of pass-by events involving heavy goods vehicles were selected in order to encompass a wide range of noise levels. The block included recordings of a range of vehicle operating conditions including steady speed pass-bys, accelerations from a constant speed and from rest and stationary idle conditions. The readings were not edited in any way so that the order of presentation and timing of events were identical to that in the original jury experiment. By adopting this procedure no order effects were expected which might confound comparisons between subjects' ratings made in the listening rooms and those made in the original experiment.

3.3 Subjects and experimental protocol

In the original experiment listeners were recruited by random selection from local electoral registers.

There were 26 jury members: 13 making ratings inside the bungalow and 13 outside. In the validation tests a total of 9 volunteers from the Laboratory staff made ratings in both the listening rooms. None had worked in the Noise and Vibration Unit. Three different listeners were used on 3 separate occasions. The instructions given to these listeners were identical to those used in the original experiment, ie they were required to rate each vehicle pass-by event on a 0 to 9 scale of increasing noisiness. A separate scale was available on a rating sheet for each event. Reference [1] gives the full text of the instructions together with an example of a rating sheet. After ratings had been made in LR1 (simulating indoor listening conditions) the listeners were asked to complete a short questionnaire on the degree of realism that had been achieved. Questions covered the visual as well as the auditory aspects of the simulation. The listeners were then transferred to LR2 (simulating outdoor listening conditions) and subjects were again instructed to rate the level of noisiness for each event. The same tape was replayed so the events and order of presentation were identical to that followed in LR1. After rating the 40 events, the listeners were asked to complete a questionnaire broadly similar to that used for LR1.

4. RESULTS AND ANALYSIS

Correlation and regression analyses were the main statistical methods used to quantify the degree of association between ratings made by listeners and noise levels achieved in the listening rooms and in the original jury experiment.

4.1 Comparison of noise levels

In each listening room the maximum noise levels and single event levels* (SEL) for each of the 40 events in terms of dB(A) and dB(C) were measured at listeners' head positions during one of the sessions. These levels were averaged and were then compared with the corresponding levels at head height achieved in the middle of the juries located inside and outside the bungalow on the test track. Figures 3 and 4 show scatterplots and corresponding regression lines for the L_{Amax} and L_{Cmax} levels measured in LR1 and inside the bungalow. Table 1 shows that the degree of correlation for both these measures and the corresponding SELs are high. It can be seen from the figures that the levels of dB(A) and dB(C) are generally higher in LR1 than in the original jury experiment.

Figures 5 and 6 show a comparison of maximum noise levels in LR2 and those measured outside the bungalow. It is clear that in this case the degree of correlation is even higher with the coefficient exceeding 0.99 in the case of A-weighted measures (Table 1). The levels obtained in this listening room were very close to those achieved at the trackside jury position over the whole range of levels examined.

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* The SEL is defined as the constant level which,if maintained for one second, would contain the same weighted noise energy as the actual event itself.

4.2 Comparison of ratings

In Figure 7 and 8 the average ratings of the 9 listeners in LR1 and LR2 are plotted against the average ratings of the jury members in the original jury experiment. Table 1 shows that correlations are again very high (>0.9) for both jury positions, although significantly lower than the best correlations obtained between the noise levels. For the inside listening conditions the average difference in ratings of −0.21 was not statistically significant.

For outside listening conditions the average difference in ratings was 0.62 which is statistically significant at the 0.1 % level of confidence.

Table 1. Correlation coefficients

Comparison	Inside	Outside
Maximum dB(A)	0.943	0.994
SEL dB(A)	0.941	0.998
Maximum dB(C)	0.904	0.965
SEL dB(C)	0.867	0.972
Ratings	0.925	0.909
Jury (odd & even)	0.974	0.959

Although part of the observed unexplained variance in the data could be attributable to differences between the original and the reproduced noise it is also possible that differences in the ratings occurred because different listeners were involved in the two experiments. This places a limit on the degree of agreement that can be expected from the two sets of ratings.

To obtain an indication of the level of agreement between jury members exposed to very nearly identical noise levels, ratings made by odd and even numbered listeners (sitting in alternate seats), positioned inside and outside the bungalow in the original experiment, were averaged separately for each of the events and the resulting sets of mean ratings were correlated. Table 1 shows the level of agreement achieved inside and outside the bungalow and indicates the limit of possible agreement between ratings in the experiments.

4.3 Questionnaire results

The results of the questionnaire completed by listeners at the end of the rating sessions in each room indicate that a reasonable level of realism was achieved in each room. A summary of the results concerning the realism of the reproduced noise is given in Table 2. Listeners considered that the sound reproduction was either "good" or "excellent" with the majority indicating that it was "excellent" in LR2.

Table 2 Summary of questionnaire results

Question	Replies	Listening room 1	Listening room 2
How realistic were the vehicle noises?	Poor Fair Good Excellent	- - 7 2	- - 3 6
Deficiencies noted	- Not enough very loud vehicles (1)* - Sounded as though noises were recorded from inside a room (1) - Difficult to disregard braking/mechanical noises (1)		- Speaker distortion (3) - Background hiss (2) - Improved with stereo sound (1)

* Number giving reply in brackets.

5. DISCUSSION

The noise levels achieved in the listening rooms were similar to those measured in the original jury experiment carried out on the test track in terms of both maximum and SEL A- and C- weighted levels. As expected the association was slightly weaker for indoor listening conditions since differences in room dimensions and furnishings led to room resonances appearing on different occasions resulting in wider differences in the noise levels observed. Despite these differences the overall level of association was good and in the case of LR2 the correlation was very high.

The ratings from the two experiments were also well related although the level of association was higher for indoor listening conditions than for the outdoor conditions. In LR2, simulating outdoor listening conditions, there was a significant tendency for ratings to be higher than in the original jury experiment. This occurred despite the fact that noise levels, as shown in Figures 5 and 6 in the two studies were very similar throughout the range of exposure examined. This effect might be a result of listeners not being fully able to adjust their ratings downwards to compensate for the fact that they were attempting to make assessments of outside noise levels while seated inside a room. Had they genuinely been outside, they would probably have expected generally greater noise levels and therefore rated the individual noise events at a lower level. Of course a constant error of this nature does not affect the correlation coefficient and is not likely to be an important consideration for future studies where ratings of relative noisiness of different vehicles will be required.

The slightly lower degree of agreement in LR2 may partly be explained by the absence of visual cues.

In the original experiment listeners in the outside jury were seated facing the vehicle emitting the noise. Although they were instructed to disregard the appearance of the vehicle it is possible that ratings were affected to some degree by, for example, vehicle size. If this is a real effect it can be argued that less biased ratings of noisiness can be expected in this listening room.

Some differences in ratings in LR1 were expected since the jury in the bungalow in the original experiment were seated throughout the room space and would have been exposed to a wider range of noise levels than the three subjects in the listening room who were seated together in a row. However, using the average scores of the 5 subjects closest to the microphone position in the bungalow the recalculated correlation was found to be almost identical at 0.929 indicating that this effect is relatively small.

A further possible reason for the observed differences is the fact that the listening room has a wooden floor which can vibrate perceptibly during noisy events while the bungalow has a concrete floor which would not have responded in this way. Such vibrations may have affected ratings in the listening room to some degree by perhaps increasing noisiness ratings at the higher noise levels.

The lack of agreement between listeners sets a limit on the degree of association that can be expected in this type of experiment. The correlations between the two halves of the jury in alternative seats for juries inside and outside the bungalow were 0.974 and 0.959 respectively. These coefficients are reasonably close to the values of 0.925 and 0.909 achieved by correlating ratings made in the listening rooms and during the original jury experiment. This indicates that a substantial portion of the unexplained variance in average scores can be accounted for by differences in the way in which listeners in the two experiments would rate identical events.

There is therefore likely to be only limited scope for improvements. Some deficiencies that if rectified might improve the degree of correlation were noted by listeners. For example, it was noted by three listeners that the sound was distorted at high levels. This can be remedied by suitable replacement speakers and amplifiers. It was also noticed that the sounds in LR1 included reverberation to some degree as if the recording had been made inside a room. A probable reason for this effect is that the original recordings outside were made close to the facade of the bungalow so that substantial reflected noise was present. This can be eliminated by making recordings in an open space, away from reflecting surfaces.

6. CONCLUSIONS

1. Listening rooms for simulating indoor and outdoor listening conditions have been successfully developed. A validation test has shown that listeners can be expected to rate the noisiness of vehicles in both these rooms in a way which closely resembles assessments made under the conditions being simulated.

2. Modifications to the recording technique and sound replay system may enhance the realism still further.

3. It is concluded that the listening rooms would provide sufficiently realistic environments for further studies of vehicle noise nuisance.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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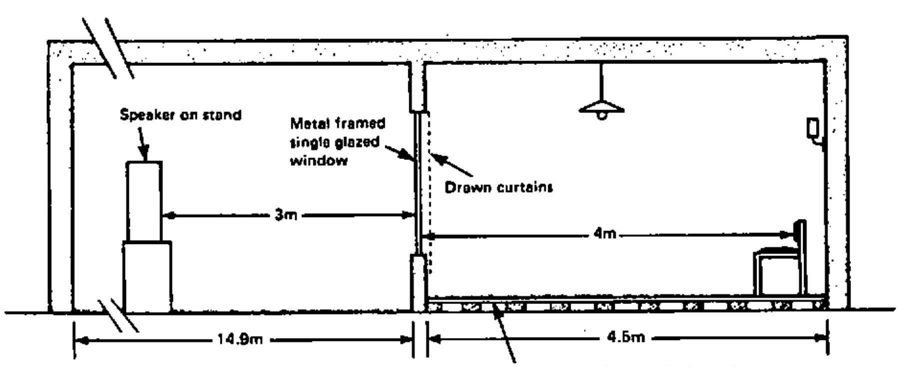

Fig.1a Listening room 1 (LR1) – simulating indoor listening conditions

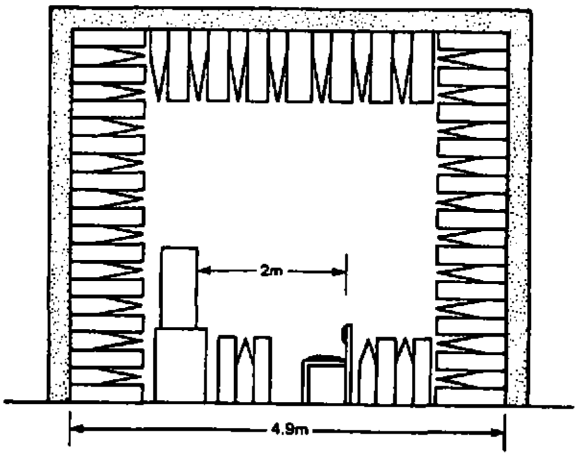

Fig.1b Listening room 2 (LR2) – simulating outdoor listening conditions

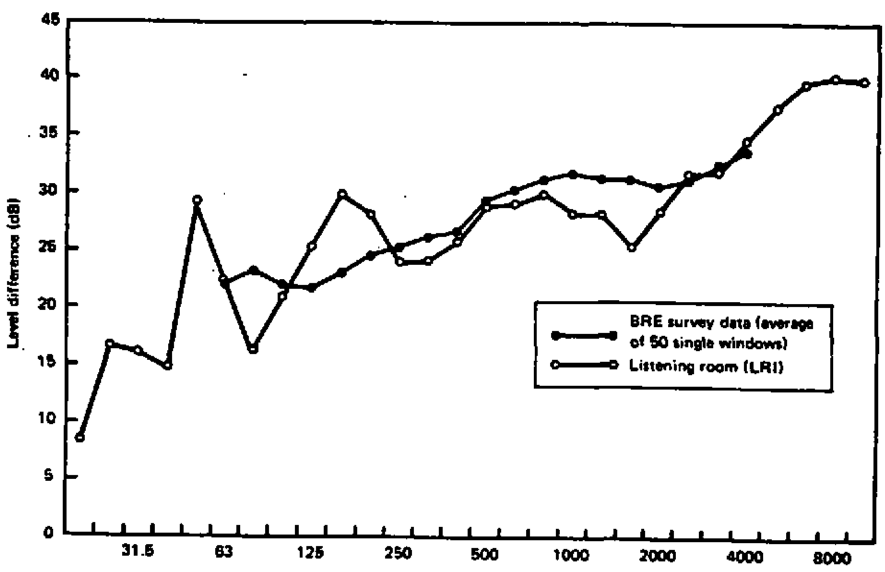

Fig.2 Level difference across window in listening room 1

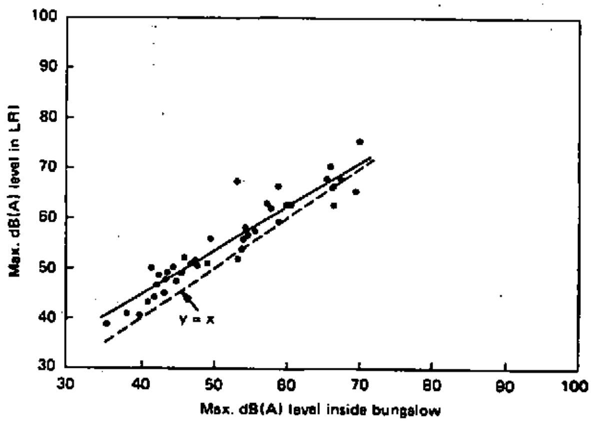

Fig.3 Maximum dB(A) level in LR1 against maximum dB(A) level inside bungalow

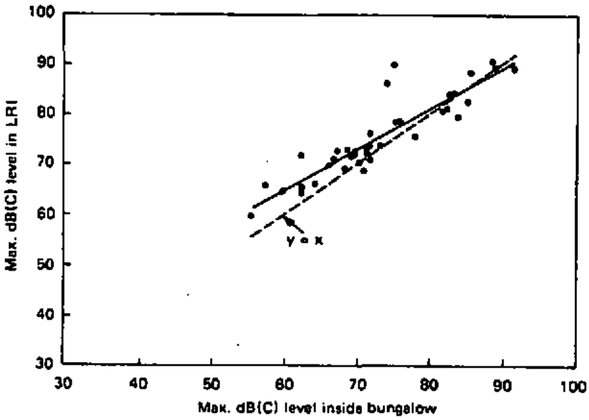

Fig.4 Maximum dB(C) level in LR1 against maximum dB(C) level inside bungalow

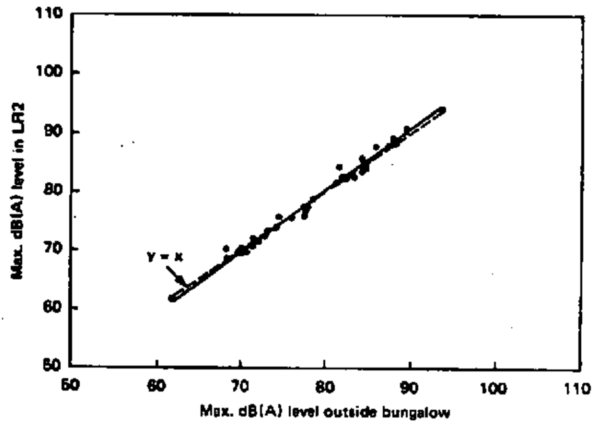

Fig.5 Maximum dB(A) level in LR2 against maximum dB(A) level outside bungalow

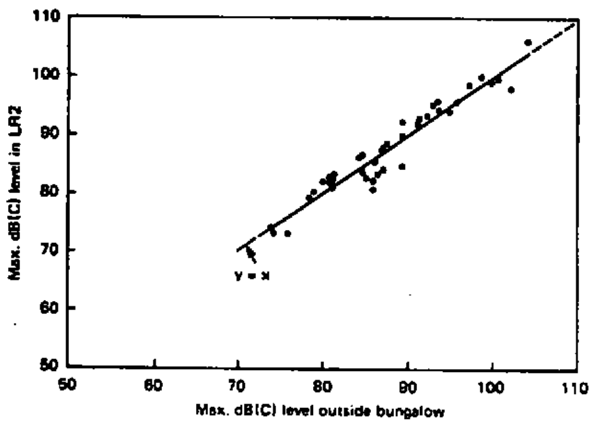

Fig.6 Maximum dB(C) level in LR2 against maximum dB(C) level outside bungalow

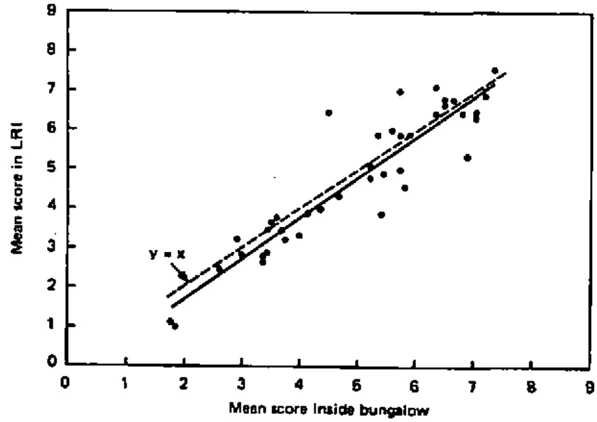

Fig.7 Mean score in LRI against mean score inside bungalow

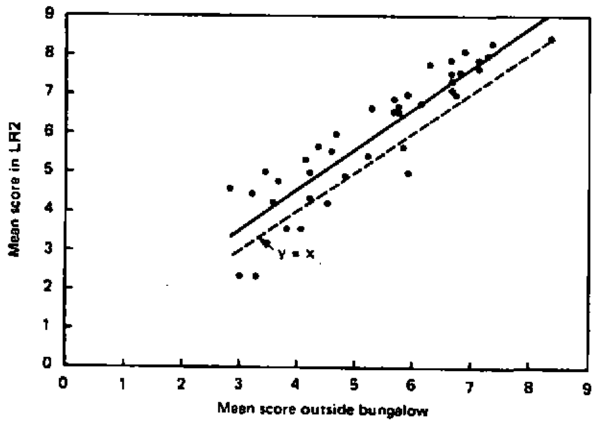

Fig.8 Mean score in LR2 against mean score outside bungalow