# Assessment of 4-2-4 and 5-2-5 Surround Sound Matrix Systems

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## 1. BACKGROUND

Although today two-channel stereo is still the most widely used way of sound distribution and emission, the new international 3/2-stereo standard according to ITU-R Rec.BS 775-1 [1] is the emerging and rapidly growing format, due to its adoption by the future digital broadcast and storage systems. It provides an additional center channel and two surround channels, completing the left and right stereo channels, thereby offering enhanced directional stability and clarity of the frontal sound image and improved realism of auditory ambience.

However, digital sound broadcasting services and links for radio and television of today (e.g. DAB, ADR, DVB, DirecTV) are still based on a two-channel layout. They make use of the bit rate reduction standard ISO/IEC 11172-3 [2] (MPEG-1 Layer II) which is recommended for two-channel sound contribution, distribution and emission purposes by ITU-R Rec. 1115 [3].

Future extension from two-channel to multi-channel transmission is considered by ISO/IEC 13818-3 [4] (MPEG-2 Layer II), which is backwards compatible with the two-channel MPEG-1 system. An MPEG-2 multi-channel bit stream can be decoded by either an MPEG-1 or an MPEG-2 decoder, according to the required reproduction properties. This configuration is shown in Fig.1-1. Down-mixing from multi-channel to two-channel stereo occurs in the encoder. Thus MPEG allows for the use of a simple two-channel MPEG-1 receiver to retrieve the encoded down mix Lo/Ro enabling the basic service with existing receivers at the lowest possible level of decoder complexity.

Backwards compatibility is achieved by the provision of compatibiliy matrices in the multi-channel encoder using appropriate down mix coefficients to create the compatible stereo signals Lo/Ro. The invers matrix to recover the five discrete stereo channels is applied in the MPEG-2 multi-channel decoder The basic matrix equations used in the encoder to convert the five input signals L, R, C, Ls and Rs into the five transport channels Lo, Ro, T3, T4 and T5 are principally according to Recommendation ITU-R BS 775-1 [1]. MPEG-2 compatibility matrixing applies dynamic switching of matrix equations in order to avoid artifacts due to the effect of unmasking, and to ensure minimum bit rates [5, 6].

MPEG broadcast systems will provide the backwards compatible multi-channel extension in the near future. This will be the step from the 2/0-stereo format to the discrete 3/2-stereo format [1] at the broadcasting site. However, it is well known that matrix solutions are successfully introduced in the two-channel broadcasting world of today, in order to provide a form of surround sound. Over a period of about ten years, the consumer 4-2-4-matrix system “Dolby Surround” has become a world leader and was in fact the only commercial success from the 1970’s experiments into quadraphony.

To provide the surround sound the incoming signals L, R, C, S are encoded through a phase/amplitude matrix to create stereo-like signals Lt and Rt. These can be treated as stereo signals for the purpose of listening, recording or transmission. When it is desired to recreate the surround sound signals they have to be decoded and these days the normal decoder is what is now known as a ProLogic decoder [7, 8].

Though the system was good for its time, it has to be acknowledged that it brought with it constraints on the way in which the surround sound dimension could be used. These constraints are the reason why discrete multi-channel surround sound is adopted for future digital broadcast services.

In a recent paper [9] it has been shown that for the introduction of multi-channel MPEG-2 sound services backwards compatibility has to be ensured not only with two-channel-MPEG-1 decoding but also with Dolby ProLogic decoding in the MPEG-1 receiver. If a programme provider is transmitting a 5-channel programme via MPEG-2, it must be possible simultaneously to provide a Dolby Surround service via MPEG-1. There is a provision within the MPEG-2 Audio specification to code the signals in a way that the backwards compatible components of the bitstream can be decoded via ProLogic, to provide Dolby surround, whilst the full bitstream is decodable via MPEG-2 decoding, to provide the full surround sound service. This combined Dolby Surround and MPEG-2 coding is depicted in **Fig. 1-2**.

The optimised Dolby Surround encoding within MPEG-2 coding eliminates some of the limitations of conventional analogue Dolby coding that were a requirement of optical film sound tracks. These details include 7 kHz-band limiting and the noise companding of the monophonic surround channel S, both of which are avoided in the MPEG scenario. The end product of this will be better Dolby Surround presentations for both stereo and surround reproduction.

It should be noted, however, that the constraints of Dolby Surround are such that specially optimised mixes of the programmes are normally required at the point of origination to overcome its limitations. If one is starting with an already balanced 3/2-stereo mix, this will not necessarily be optimum for Dolby Surround. The end product will be different sound presentations from the Dolby Surround and the full 5-channel services, but at least both sets of listeners will receive some form of surround sound.

The original 5-channel presentation is, however, not changed at all by the above process, and the decoded representation of the original sound sources is precisely what was intended by the producer.

Since about one year there is a new generation of multi-channel matrix systems on the market. It is claimed that digital processing and special matrix technology results in improved multi-channel sound presentation, in particular minimised constraints compared with Dolby Surround:

- Decoding of stereo surround signals Ls and Rs instead of mono surround signal S
- Transmission of 3/2-stereo final mixes (no encoder/decoder monitoring at the mixing stage)
- Optimum 2/0-stereo downwards compatibility (optimum Lt/Rt downmix)

  Compatibility with Dolby ProLogic decoders

Obviously the performance claimed here would be interesting in combination with MPEG-2 coding (see **Fig. 1-2**), because it would be possible to encode any 3/2-stereo material without constraints due to the requirement of backward compatibility with Dolby Surround.

It is the purpose of this paper to study the performance of the two new 5-2-5-matrix systems “Circle Surround” [10] and “Lexicon Surround” [11, 12], in comparison with 4-2-4 Dolby Surround [13], with respect to the possible application in MPEG-2 coding.

## 2. ASSESSMENT OF THE QUALITY OF MATRIX SYSTEMS

For these tests the matrix systems are treated as systems which have to transmit a 5-channel recording via a 2-channel line. This means that specially optimised mixes of the programmes (according to the limitations of e.g. Dolby Surround, as mentioned above) are not used. This is exactly what is required by the combined Dolby Surround and MPEG-2 coding as shown in **Fig. 1-2**: It is mandatory that the MPEG-2 decoded discrete 3/2-stereo representation of the original sound sources is precisely what was intended during the origination process.

Three tests were performed:

**Test 1:** Performance of Circle / Dolby / Lexicon surround multi-channel codecs (see **Fig. 2-1**)

**Test 2:** Compatibility of Circle and Lexicon Encoder with ProLogic Decoder (see **Fig. 2-2**)

**Test 3:** Downwards compatibility (see **Fig. 2-3**)

As mentioned above, the MPEG-2 Audio specification provides a special encoder matrix to code the signals in a way that the backwards compatible components of the bitstream can be decoded via MPEG-1 and subsequently via ProLogic, whilst the full bitstream is decodable without artifacts via MPEG-2 decoding. (see **Fig. 1-2**). An optimised Dolby Surround encoder for digital transmission is provided which avoids some of the limitations, in particular 7 kHz-band limiting and noise companding (in this paper it is called “Dolby Surround Plus”). It could be expected that this encoder could improve the quality of the two-channel stereo presentation Lt/Rt, whilst allowing usual ProLogic decoding.

The “ Dolby Surround Plus” encoder was inserted in the downwards compatibility test (Test 3), in order to verify its performance in comparison with Circle, Lexicon and Dolby Surround encoder.

## 3. THE TESTED MATRIX SYSTEMS

CIRCLE SURROUND [10]

Equipment: Circle Surround 5.2.5 Static Encoder, 5.2.5 Decoder
Features: Stereo surround, full frequency range in all channels

Encoding: L, R, C according to ITU-R BS 775-1 [1]
LS, RS ⇒ Phase shift (90°) ⇒ according to their level difference ⇒ Lt /Rt

Decoding: Dominant signals in several frequency ranges are detected and accordingly processed. It is possible to produce two signals with different frequency ranges for in the surround speakers. Pumping effects should be eliminated with this technique.

LEXICON SURROUND [11, 12]

Equipment: 2x Lexicon DC1 (modified, version 07.97)
Features: Stereo surround, full frequency range in all channels

Encoding: L, R, C according to ITU-R BS 775-1 [1]
LS, RS ⇒ Phase shift (90°) ⇒ according to their level difference ⇒ Lt /Rt
Monitoring of the level ratio of front/back: if surround level is 3 dB less than front level, the surrounds will supply the Lt/Rt with diminished level. This should fulfil the conditions of the official MPEG-downmix, where the surrounds are mixed with -3 dB to the front channels.

Decoding: Again, dominant signals are detected and processed according to their direction. Simultaneously appearing decorrelated signals are not influenced by this processing.

DOLBY SURROUND [7, 8]

Equipment: Dolby SEU4, SDU4 (ProLogic)
Features: Mono-Surround, 7kHz lowpass and compression system in the surround channel

Encoding: L, R, C according to ITU-R BS 775-1 [1]
Lt = L + 0.7 (C - jS); Rt = R + 0.7 (C + jS)

Decoding: 'Dominant signals' are detected and processed according to their direction (left/right, front/back), the surround signal is additionally lowpass filtered at 7 kHz, and delayed according to the reproduction room size. Only one dominant signal can be processed at a time.

"DOLBY SURROUND PLUS" ENCODER (Test 3 only, "Dolby+")

Equipment: Dolby Surround Plus Encoder
Features: Mono-Surround, no 7kHz lowpass and compression system in the surround

Encoding: L, R, C according to ITU-R BS 775-1 [1]
Lt = L + 0.7 (C - jS); Rt = R + 0.7 (C + jS)

# 4. TEST MATERIAL

The test material represents a selection of 3/2-stereo recordings. The selection of this material was made in co-operation with the manufacturers. Each party was invited to make suggestions concerning the test material. Finally, nine items were chosen, as listed in **Table 1**.

| Tr. | Item | Interpret/titel | Information/ | Charcteristics | Production | Dura |
|---|---|---|---|---|---|---|

| | | | Location | | | tion |
|---|---|---|---|---|---|---|
| 1 | pop | Earth, Wind & Fire | centre not used | two channel stereo with stereo surround effects | From Dolby Test Disc | 19 s |
| 2 | gospel | The Jackson Singers | Kreuzkirche Dresden | live concert atmosphere, lead singer and rhythm combo in the centre | Telekom 1995 | 23 s |
| 2 | gospel | The Jackson Singers | Kreuzkirche Dresden | live concert atmosphere | Telekom 1995 | 23 s |
| 3 | film | Batman Forever | | typical film sound effects, rotating sound source (helicopter) | T. Burton, Warner Bros | 11 s |
| 4 | icehockey | | ambience microphone | stadion live atmosphere, commentary in the centre | IRT 1994 | 23 s |
| 5 | audience | | | typical audience noise during a break in a concert hall | Bayerischer Rundfk. 1994 | 18 s |
| 6 | applause | | | applause in a concert hall | BBC | 17 s |
| 7 | chorus | Dallas Symphony Orchestra & Chorus (Tschaikowsky, Overture 1812) | | start with one chorus in the sur-rounds, during the item introduction of another chorus in the front | Delos | 21 s |
| 8 | ensemble | | | transparent recording of a small ensemble with discrete room response in the surrounds | | 23 s |
| 9 | orchestra | Gewandhaus Orchester Leipzig (Mussorgsky, Pictures of an Exhibition) | Gewandhaus Leipzig | recording of a great orchestra with natural room response of the concert hall in the surrounds | Telekom | 22 s |

**Table 1** Test material list

The audio material was en- and decoded with the different systems and then edited on a „Pro Tools“ system (**Fig. 41**). Again each of the manufacturers was asked to participate in the adjustment of his system. This was actually done, except the Dolby units. They could be adjusted according to the owner's manuals.

After the special line-up some systems needed, the 'whole transmission system' was aligned. All inputs of the units were fed with decorrelated pink noise. Finaly, the SPL of each channel, then of all channels together was measured via the whole playback system, including amplifiers and loudspeakers.

The Lexicon encoder was supplied with digital signals, the other two encoders with analogue signals. For the Dolby system the surround input signals Ls and Rs were summed to the mono surround signal S (see also **Figs. 2-1, 2-2, 2-3**). In these cases the two playback surrounds were fed both by the mono surround S, according to the recommended praxis [7]. Corresponding level correction was provided.

All test sequences were recorded on a 8-track Sony PCM 800.

## 5. TEST SET-UP

The set-up of the surround sound and stereo tests are shown in **Fig. 5-1a** and **Fig. 5-1b**. In both cases the listening positions have to be considered as an optimum. That implies that the derived results are only valid for the optimum listening positions. The dependence on critical listening positions was not investigated.

A subwoofer/satellite combination was employed. In detail the set-up consists of 5 monitor loudspeakers of the same type (Klein&Hummel O108) and two subwoofer units (Genelec 1094A in combination with the three front speakers and Genelec 1092A in combination with the two surround speakers) (**Fig. 5-1**).

The electro- and room-acoustical quality parameters meet the requirements of ITU-R BS.1116 [13].

The calibration of each channel was achieved by a pink noise signal. The loudness balance between the test items was adjusted subjectively. Besides the objective calibration of the discrete 5 channels and the matrix systems under test by a pink noise signal the settings were controlled subjectively using the test items. Objective and subjective calibration were identical in all cases except the Dolby surround systems. The Dolby system required an increase in listening level of 2 dB referring to the objective measurement. Generally the adjusted listening level was 5 to 10 dB below the reference listening level of 85 dBA defined in ITU-R BS.1116 [13].

# 6. TEST METHOD

In the case of surround sound as well as in the case of stereo the listening tests were introduced by an extensive training phase. During this training phase the kind of impairment to be assessed were demonstrated and the test method was exercised.

### 6.1 Coded/decoded Surround Sound

A modified version of the well-known 'Triple Stimulus with Hidden Reference' according to ITU-R BS.1116 [13] was used. This method was developed to discover small impairments between the systems under test. The listening tests were carried out as group tests (three listeners at each test). We presented four stimuli ('A-B-C-A') in which the known reference is always 'A'. The hidden reference is randomly assigned to 'B' or 'C'. The listener now has to assess 'B' and 'C' in relation to 'A' on the five-grade impairment scale given in Rec. ITU-R BS.562 [14] (see below). The recognized hidden reference must be assessed with '5' whereas any difference between the system under test and the reference must be interpreted as an impairment (see **Fig. 6.1-1**).

| Impairment | Grade |
|---|---|
| Imperceptible | 5 |
| Perceptible, but not annoying | 4 |
| Slightly annoying | 3 |
| Annoying | 2 |
| Very annoying | 1 |

### 6.2 Downwards Compatibility

In the two-channel compatibility test we used another test method because of the missing 'reference'. When using the 5-channel mix as a reference, the listeners probably always will prefer it instead of the 2-channel mix. A modified 'Double Stimulus Quality Method' according to Rec. ITU-R BT.500 [15] was applied: The quality of the stimuli „A" and „B" have to be assessed by means of the quality scale corresponding to Rec. ITU-R BS.562 [14]. To relate to the standard downmix (according to Rec. ITU-R BS.775-1 [1]), the 'A-B' sequence was a randomly distributed combination of Lt/Rt and the standard downmix (see also **Fig. 6.2-1**).

| **Quality** | **Grade** |
|---|---|
| Excellent | 5 |
| Good | 4 |
| Fair | 3 |
| Poor | 2 |
| Bad | 1 |

# 7. RESULTS

## 7.1 Coded/decoded Surround Sound

7.1.1 Performance of Circle / Dolby / Lexicon Surround Multichannel Codecs

The analysis of the surround sound tests (4-2-4 respectively 5-2-5 matrix and 4-2-ProLogic respectively 5-2-ProLogic) was done by calculating the SDG (subjective diff grade = obj grade - ref grade) for each listener and test item. Based on the SDG the average and 95% confidence interval was calculated for each test item. The graphical representation of the averages and 95% confidence intervals allows some remarks about the significance of the observed differences. If there is no overlapping of the confidence intervals it usually can be assumed that the differences are significant. On the other hand the observed differences are assumed not to be significant if the confidence intervals overlap. These hypothesises however have to be checked by carrying out a corresponding significance test. In the considered case, working with rank scales and dependent probes, the Wilcoxon test is adequate. The Wilcoxon test analyses in pairs if two probes differ significantly referring to a presumed significance level. The calculations were done for a one-sided test and a significance level of 5 % ($P1<0.05$). The determined significant differences are indicated in the presented diagrams. The analysis includes 18 assessments in each case. Two listeners were excluded, because they did not meet the reliability requirement defined in 8.3.

The resulting group of listeners consists of 9 sound engineers and 9 music students. A separate analysis was done for the sound engineers. Compared to the overall analysis the sound engineers seem to prefer „clear" assessments. That means they show a tendency to assess a „good" performance „slightly better" and a „bad" performance „slightly worse" than the whole group. A separate analysis is not presented because the observed differences are not significant.

The results for the 4-2-4 (Dolby Surround) and 5-2-5 matrix systems (Circle and Lexicon Surround) are shown in **Fig. 7.1-1**.

The results with respect to the overall quality of the tested matrix systems (encoded and decoded) show that the performance of the tested matrix systems strongly depend on the test item. Regarding 30% of the test items (applause, gospel, icehockey) there is no significant difference between the matrix systems. The performance is rather poor (-3 = annoying...-2 = slightly annoying) compared to the reference 3/2-stereo recording. Regarding the remaining 6 test items significant differences are observed resulting in a significantly better assessment of the 5-2-5-systems. The following table shows the analysis of the preferences:

| | **percentage of preference re** | | |
|---|---|---|---|
| | Circle | Dolby | Lexicon |
| Circle | --- | 0% | 33% |
| Dolby | 33% | --- | 42% |
| Lexicon | 0% | 0% | --- |
| **sum** | 33% | 0% | 75% |

Regarding the 6 test items with a significant improvement by 5-2-5 matrixing the Lexicon system is preferred 75 % of the cases. On the other hand the 4-2-4 system (Dolby surround) is not preferred at all.

7.1.2 Compatibility of Circle and Lexicon Encoder with ProLogic Decoder

The results for the systems under test using the ProLogic Decoder (5-2-ProLogic respectively 4-2-ProLogic = 4-2-4) are presented in **Fig. 7.1-2.**

Although significant differences are observed in two cases (gospel, icehockey) the results appear uniquely. Except one test item (icehockey) there are no significant differences between Dolby and Circle / Lexicon. That means that the 5-2-5 matrix systems under test are Dolby compatible. Compared to the 3/2 reference the performance meets the Dolby quality level (-3 = annoying...-2 = slightly annoying)

## 7.2 Reliability and Reproducibility

The „Triple stimulus with hidden reference“ method is based on grading the hidden reference „B“ or „C“ 5 and the test object 1....5 referring to the perceived impairment. Thus the calculation of the SDG (subjective diff grade = obj grade - ref grade) leads to negative SDG. Positive SDG could be interpreted as „wrong“ assessments because reference and test object were obviously exchanged. A percentage of more than 10 % of totally 50 test sequences was considered as not acceptable. This criterion leads to exclude 2 listeners. The resulting analysis is now based on 18 listeners.

In order to control the reproduction of the results 5 of totally 50 test sequences were repeated. The corresponding averages, 95 % confidence intervals and Wilcoxon test results are presented in **Fig. 7.2-1.** The results show that a good reproduction of the results is achieved. No case of significant difference is observed regarding the corresponding results.

## 7.3 Downwards Compatibility

Considering the reasons mentioned above the Lt/Rt assessment was carried out by means of a modified „Double stimulus quality method“ based on ITU-R BT.500 [15]. In each case one of the stimuli „A“ or „B“ was the downmix referring to ITU-R BS.775 [1]. Because a reference could not

be defined the analysis is not done by means of SDG but individual averages and 95 % confidence intervals in each case.

The results of the Lt/Rt signals (Circle, Dolby, Lexicon, Dolby+) and the corresponding standard downmixes are presented in **Fig. 7.3-1**.

Considering 4 of 8 test items (ensemble, gospel, icehockey, orchestra) there is no significant difference between the Lt/Rt signals and the corresponding standard downmix. The performance covers the quality level (3 = fair...4 = good). Considering the remaining 4 test items a significant difference is observed resulting in a better performance of the standard downmix. Regarding the statistics of preference the following result is derived.

| | **Percentage of preference re** | | | | |
|---|---|---|---|---|---|
| | ITU-R 775 | Circle | Dolby | Lexicon | Dolby+ |
| ITU-R 775 | --- | 0% | 0% | 0% | 0% |
| Circle | 12.5% | --- | 0% | 0% | 0% |
| Dolby | 25% | 0% | --- | 0% | 0% |
| Lexicon | 25% | 0% | 0% | --- | 0% |
| Dolby+ | 12.5% | 0% | 0% | 0% | --- |
| **sum** | 75% | 0% | 0% | 0% | 0% |

In the case of a significant difference between Lt/Rt and the ITU-R 775 downmix, the ITU-R 775 downmix shows the better stereo performance. This concern 50 % of the test items. However it must be stated that the test method could lead to a magnification of the observed quality differences.

# 8. SUMMARY OF RESULTS

The performance of the two new 5-2-5-matrix systems “Circle Surround” [10] and “Lexicon Surround” [11, 12] was tested, in comparison with 4-2-4 Dolby Surround [13], with respect to the possible application in MPEG-2 coding. Main results are:

1) The new 5-2-5 matrix systems allow improved quality of coded/decoded surround sound for individual sequences.
2) Compatibility of Circle Surround and Lexicon Surround Encoders with ProLogic Decoder has been shown
3) Optimum downwards compatibility 3/2 → 2/0 is achieved by the standard downmix according to ITU-R BS 775-1 [1].
4) It could not be verified that the optimised Dolby Surround encoder for digital transmission (“Dolby Surround Plus”) could improve the quality of the two-channel stereo presentation Lt/Rt.

## REFERENCES

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[14] ITU-R: "Subjective assessment of sound quality". Recommendation ITU-R BS.562-3 (1988).

[15] ITU-R: "Methodology for the subjective assessment of the quality of television pictures". Recommendation ITU-R BT.500-6 (Draft, 1994).

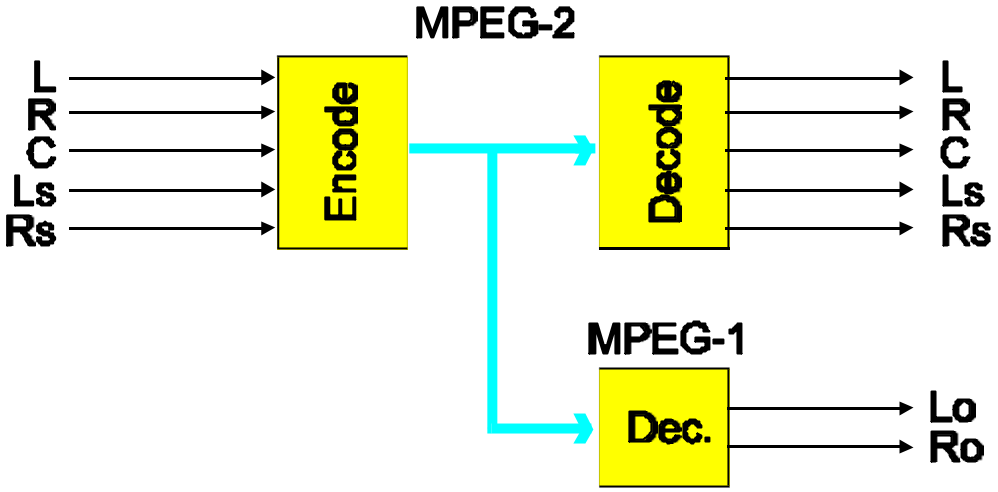



**Fig. 1-1** Backwards compatible MPEG-2 discrete digital surround sound

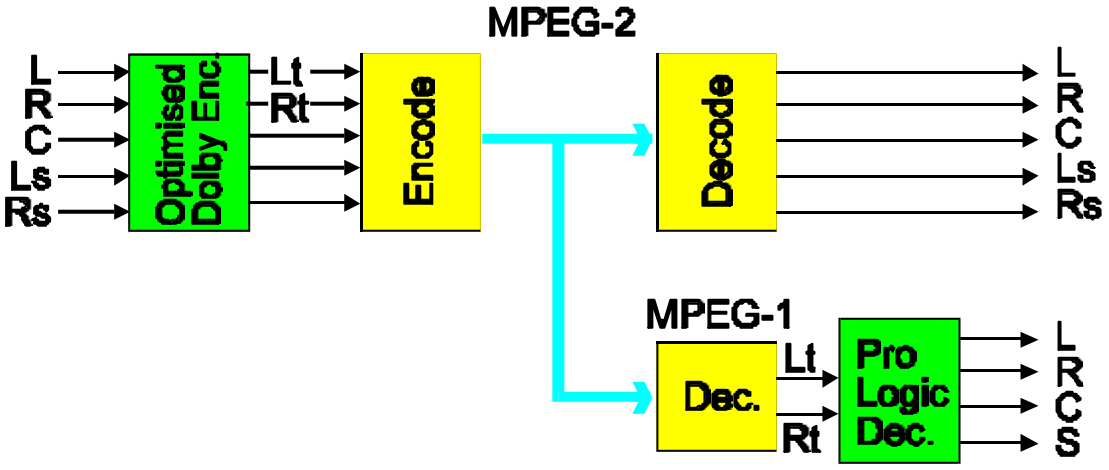



**Fig. 1-2** Combined Dolby Surround and MPEG-2 coding

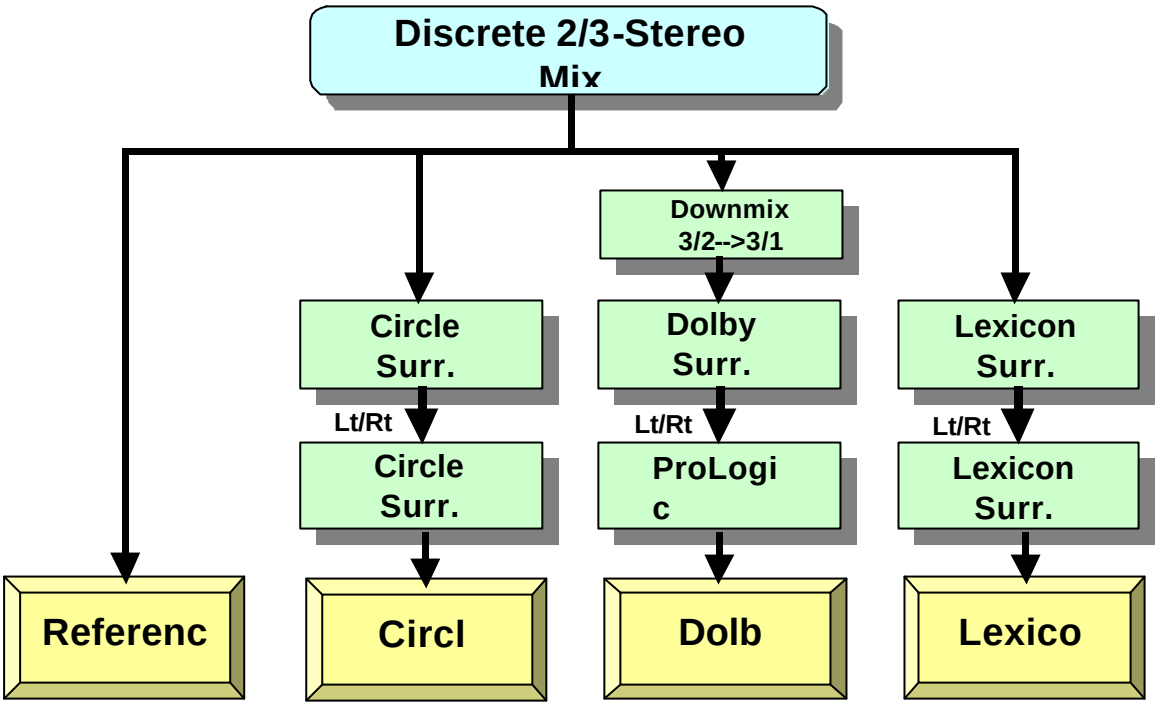



**Fig. 2-1** Test 1: Performance of Circle / Dolby / Lexicon surround muli-channel codecs

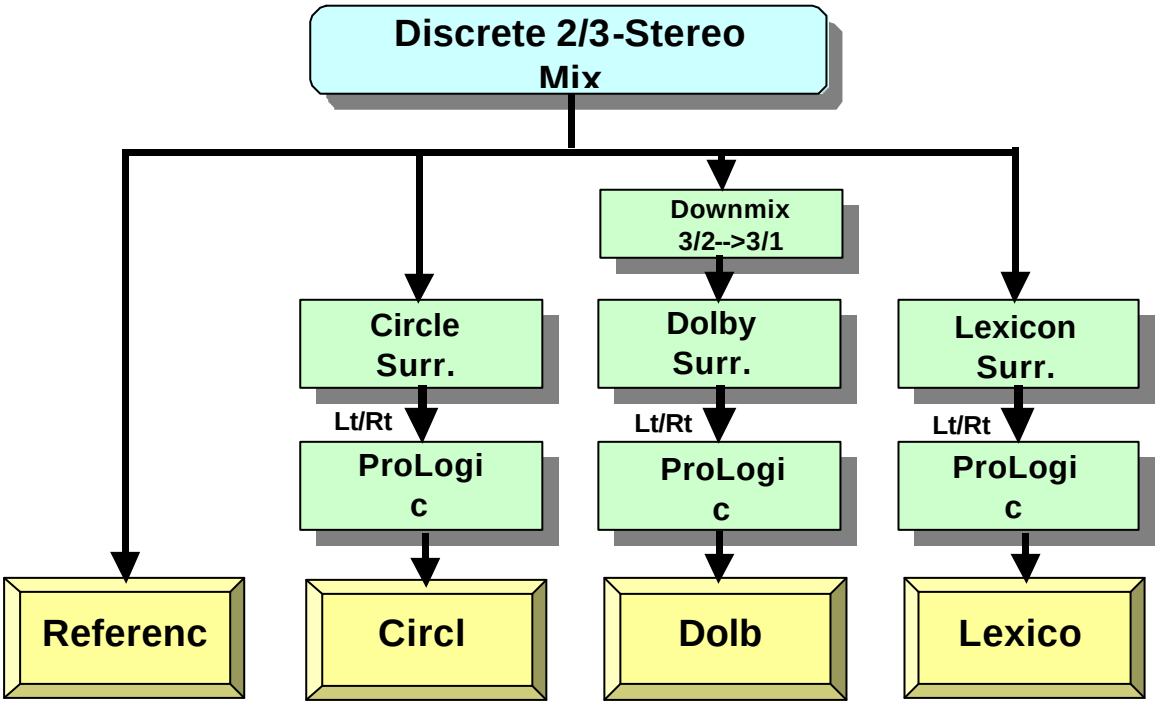



**Fig. 2-2** Test 2: Compatibility of Circle and Lexicon Encoder with ProLogic Decoder

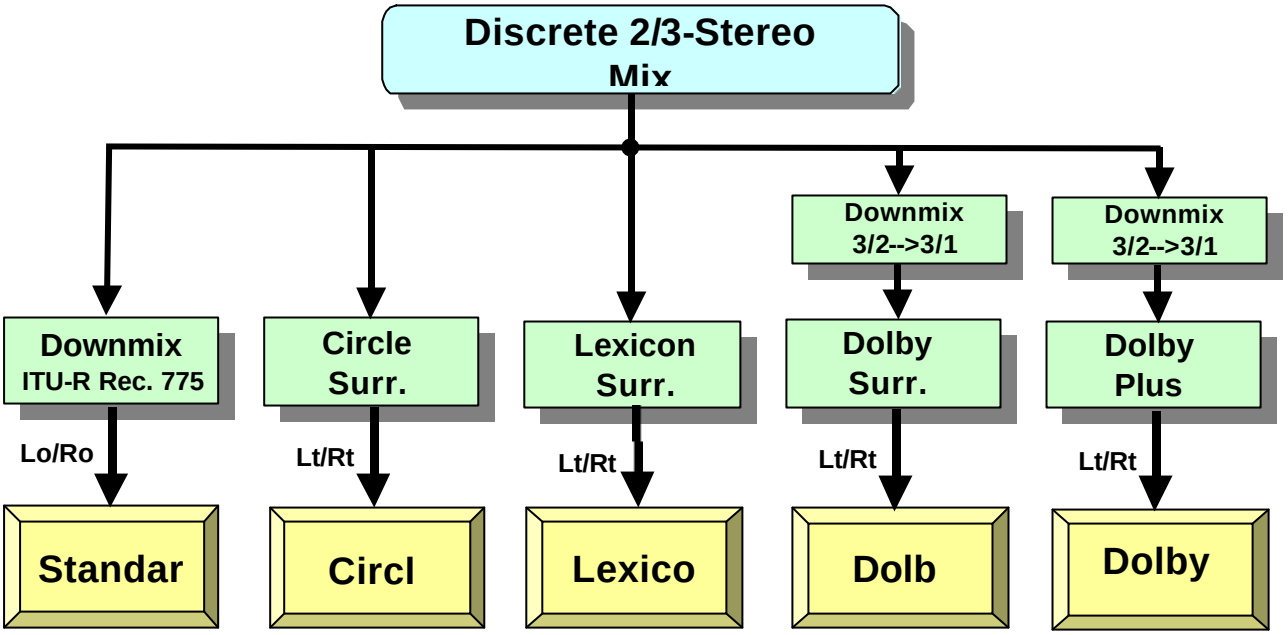



**Fig. 2-3** Test 3: Downwards compatibility

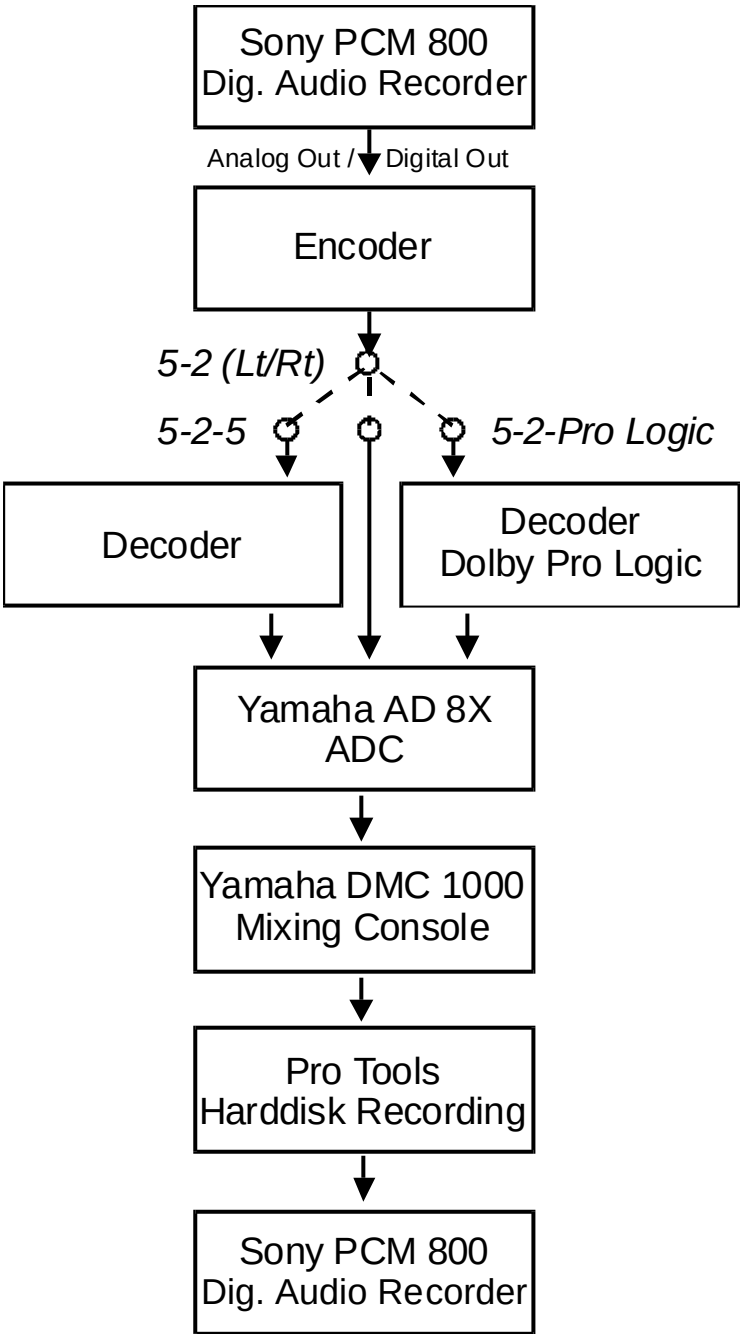



**Fig. 4-1** Generating and editing of the test items

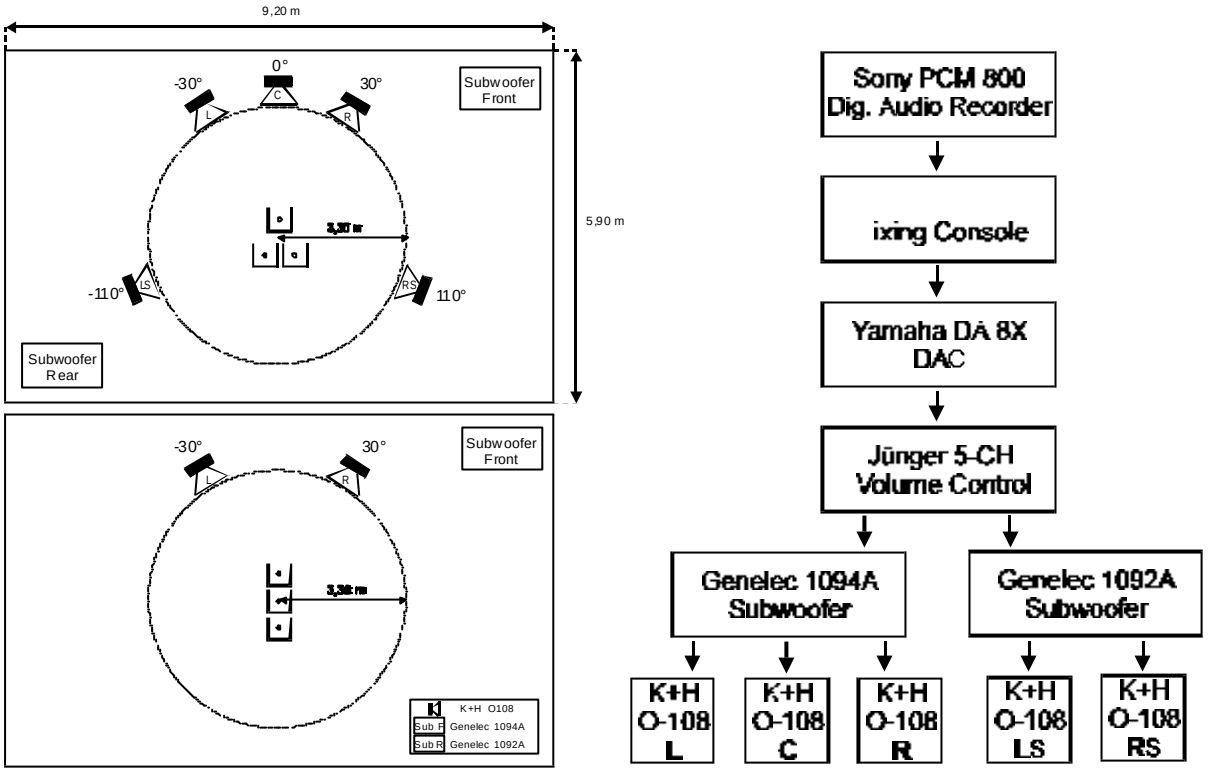
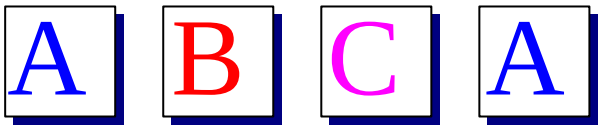



**Fig. 5-1** Test set-up.
**a**: Decoded surround sound (above) **b:** Lt/Rt compatibility (below)

## Method "A-B-C-A"

modified "Triple Stimulus with hidden reference"

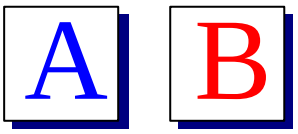



- A=REFERENCE
- Assessment of B ***and*** C compared to A
- B or C is the hidden REFERENCE

**Fig. 6.1-1...** Test method. Surround sound

## Method "A-B"

ITU-R BT.500 modified




- Assessment of A ***and*** B
- A and B randomly presented pair of Lt/Rt and ITU-R775 downmix

**Fig. 6.1-2...** Test method: downwards compatibility

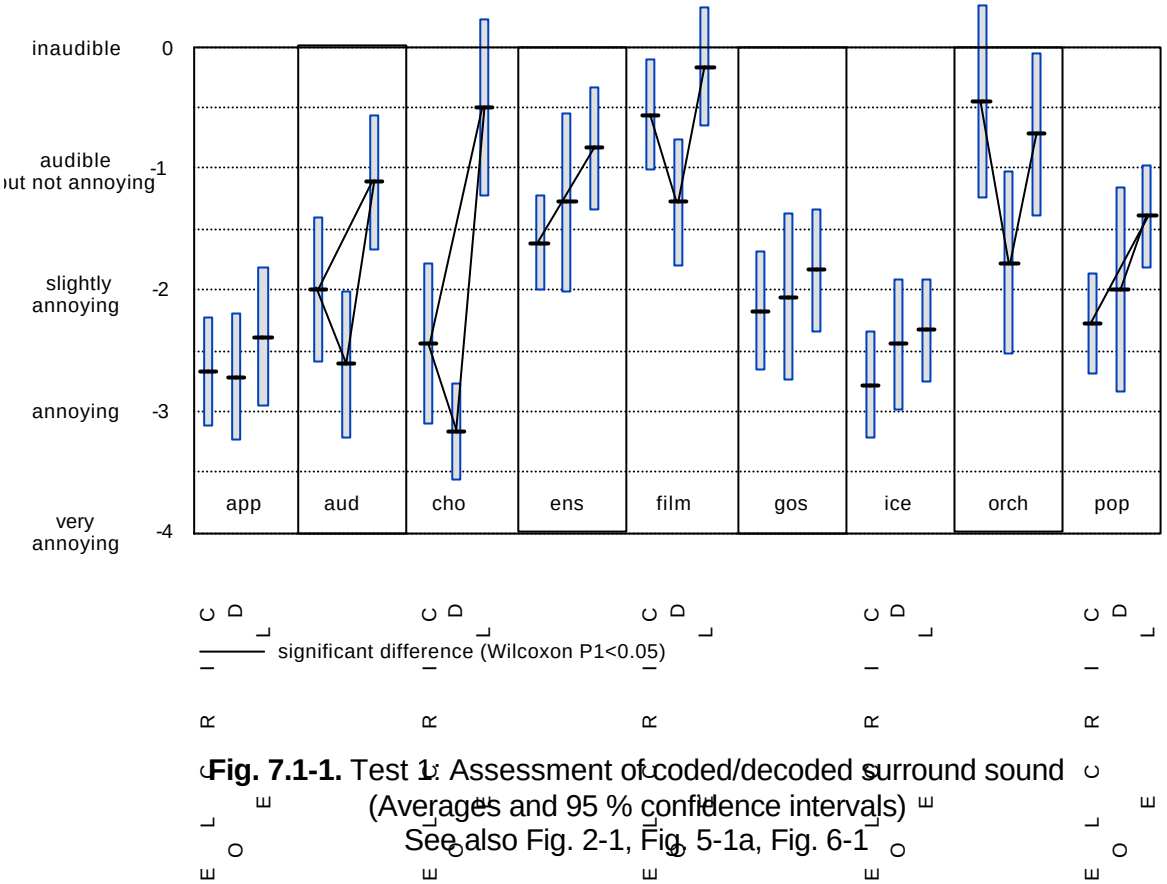



**Fig. 7.1-1.** Test 1: Assessment of coded/decoded surround sound (Averages and 95 % confidence intervals)
See also Fig. 2-1, Fig. 5-1a, Fig. 6-1

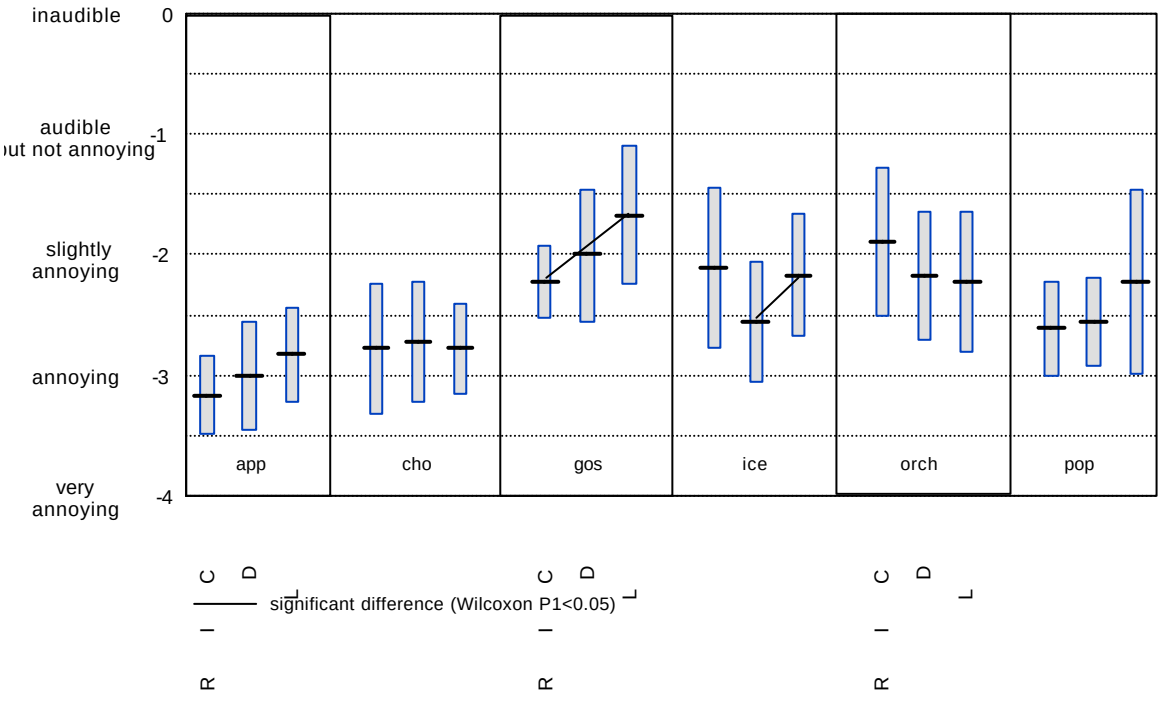



**Fig. 7.1-2** Test 2: Compatibility of Circle and Lexicon Encoder with ProLogic Decoder (Averages and 95% confidence intervals)
See also Fig. 2-2, Fig. 5-1a, Fig. 6.1-1

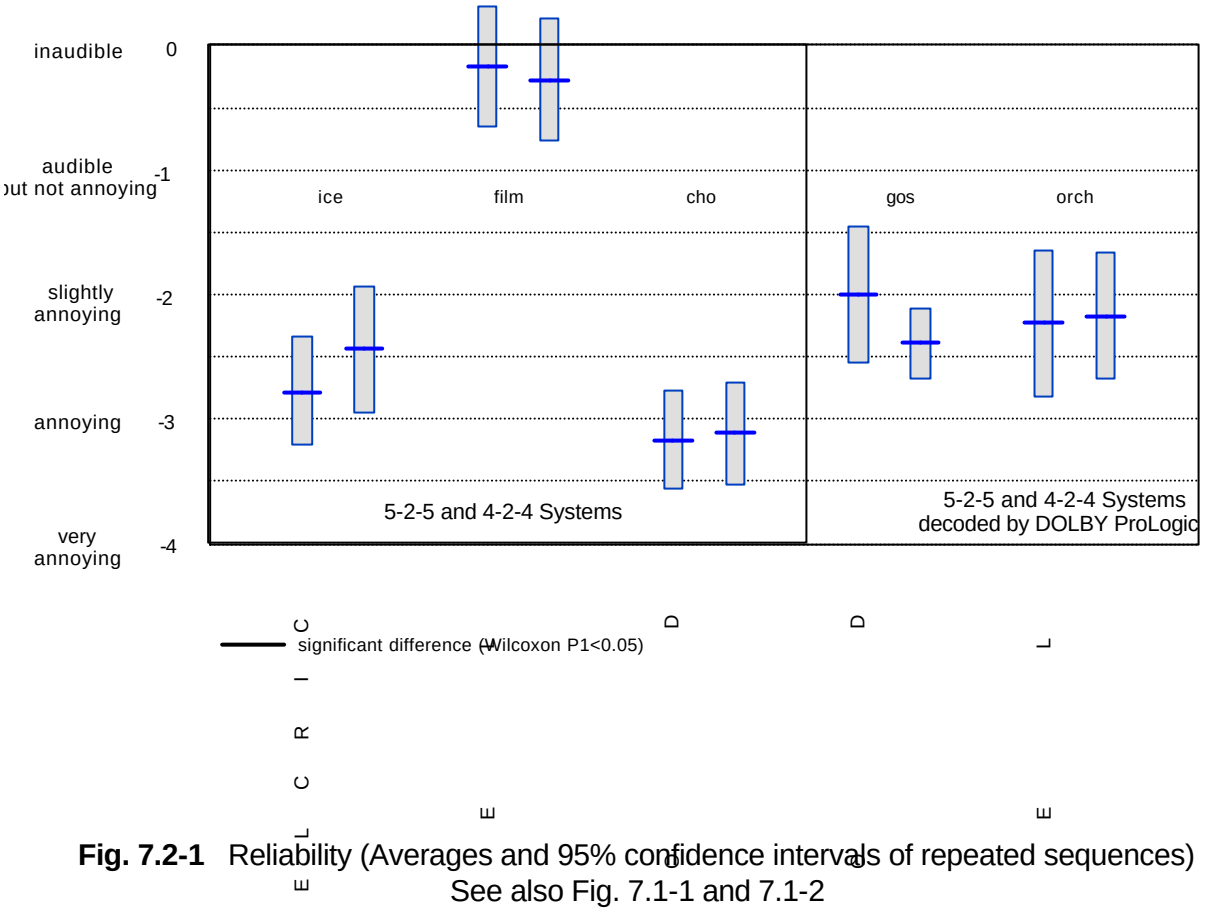
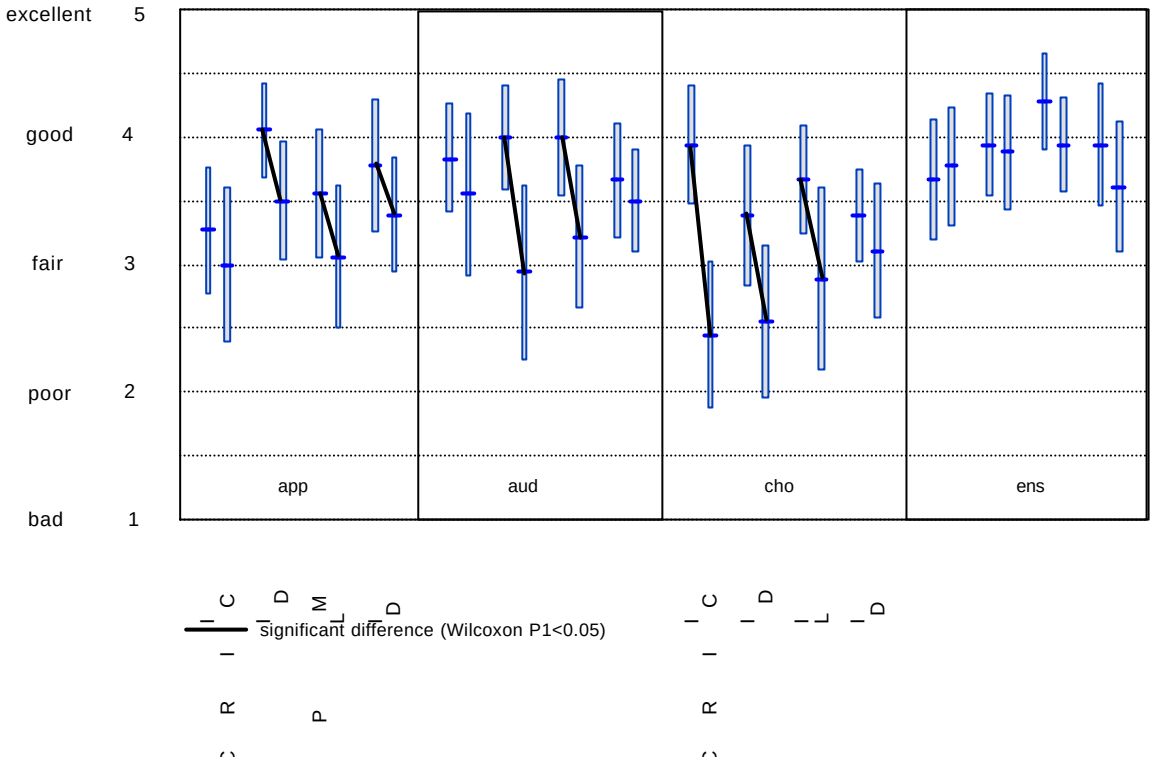



**Fig. 7.2-1** Reliability (Averages and 95% confidence intervals of repeated sequences)
See also Fig. 7.1-1 and 7.1-2



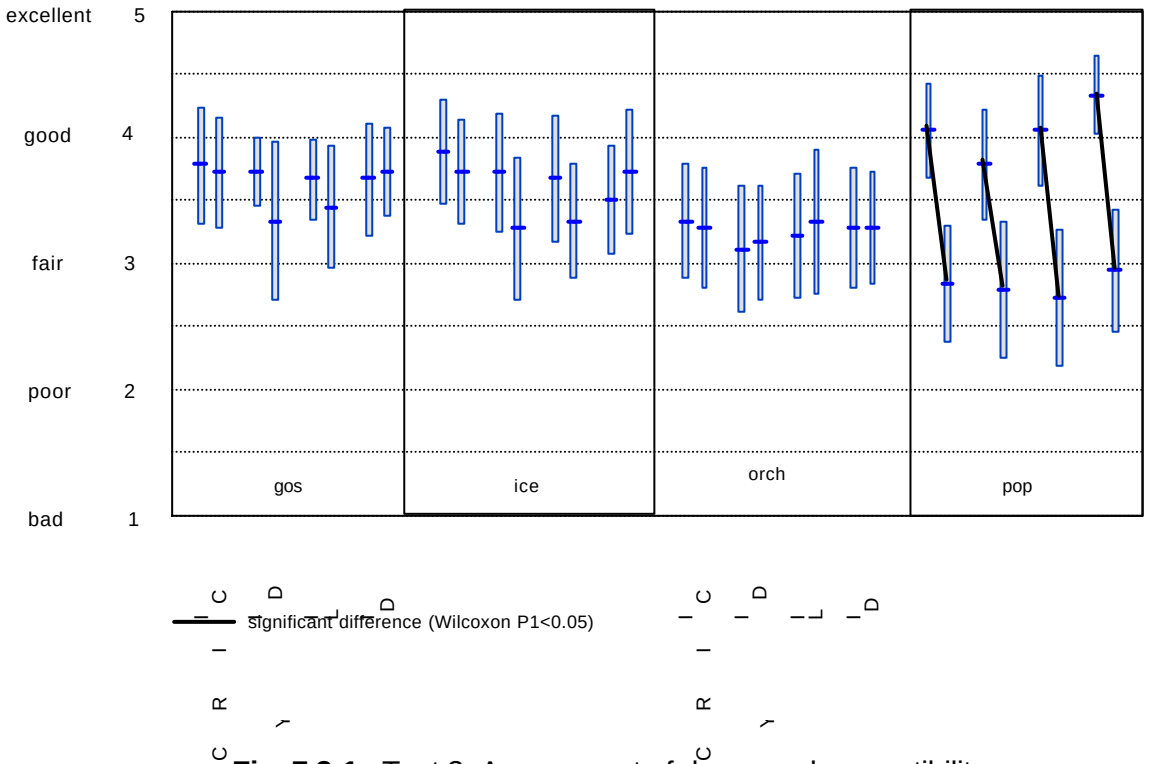




**Fig. 7.3-1** Test 3: Assessment of downward compatibility
(Averages and 95% confidence intervals)
See also Fig. 2-3, Fig. 5-1b, Fig. 6.2-1