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Results of a Semantic Differential Test to Evaluate HVAC&R Equipment Noise

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Acknowledgement

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- Also thanks to fellow graduate students at Herrick Labs.
  - Jelena Paripovic and Daniel Carr

Introduction

- HVAC&R equipment noise can be annoying
- Possible Noise induced sleep problems
  - e.g. Passchier-Vermeer & Passchier, 2000
- HVAC&R noise can have a negative effect on work efficiency
  - e.g. Holmberg, 1997

Mobile Truck

https://www.anstertrailer.com/product/refrigerated-truck-trailers/

Residential

http://www.goodmanmfg.com/products/air-conditioners

Introduction

Vehicle HVAC systems

- Zwicker Loudness and annoyance highly correlated (Leita & Paul, 2009; Hohls *et al.*, 2014)
- Articulation Index, Roughness, Sharpness are correlated with preference (Leita & Paul, 2009; Hohls *et al.*, 2014)

Air-conditioning and refrigeration Equipment

- Sound Quality Indicator: tone penaltied loudness metric (ANSI/AHRI 1140, 2012)

Fan

- Zwicker Loudness and annoyance highly correlated (Susini *et al.*, 2004; Schneider and Feldmann, 2015; Naji and Sanan, 2015)
- Tonalness of fan noise (Gerard *et al.*, 2005; Yamaguchi *et al.*, 2014)

Compressor

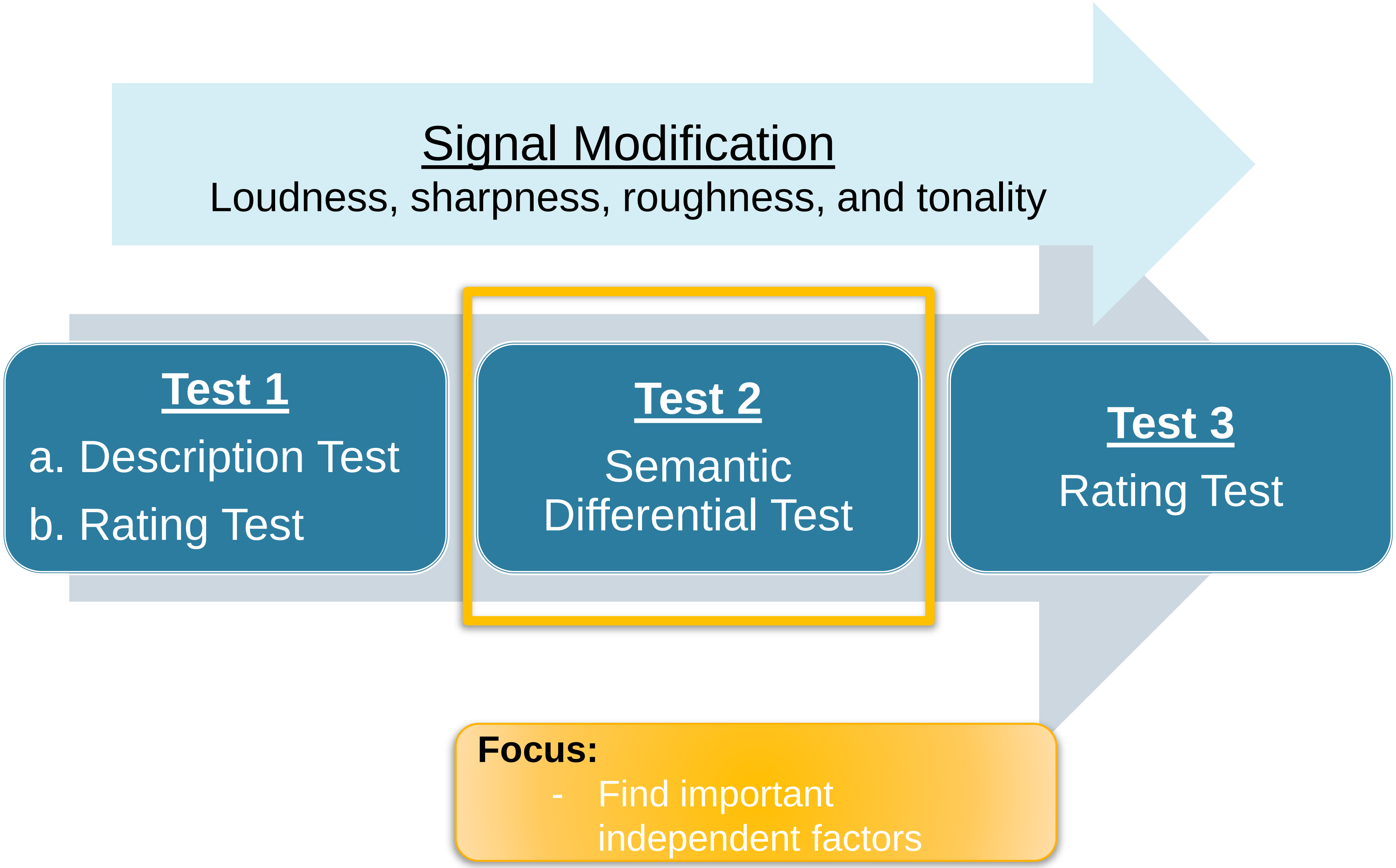
- Sharpness and beating affect sound quality (Wang, 1994)

Diesel Engine

- Impulsiveness metric affects annoyance (Russell & Haworth, 1985; Champaign & Shian, 1997; Hastings, 2004; Bodden, 2005)

Goal: To develop a sound quality model that predicts annoyance due to HVAC&R equipment noise

Overview of the Subjective Tests



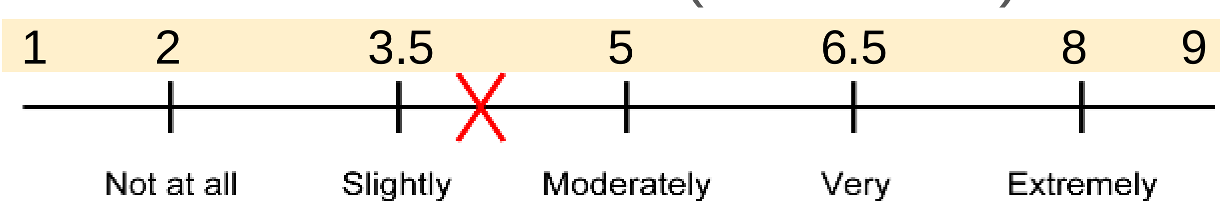
Previous Test (Sung, Davies, and Bolton, 2017)

- Part A – Describe the sounds (36 sounds)

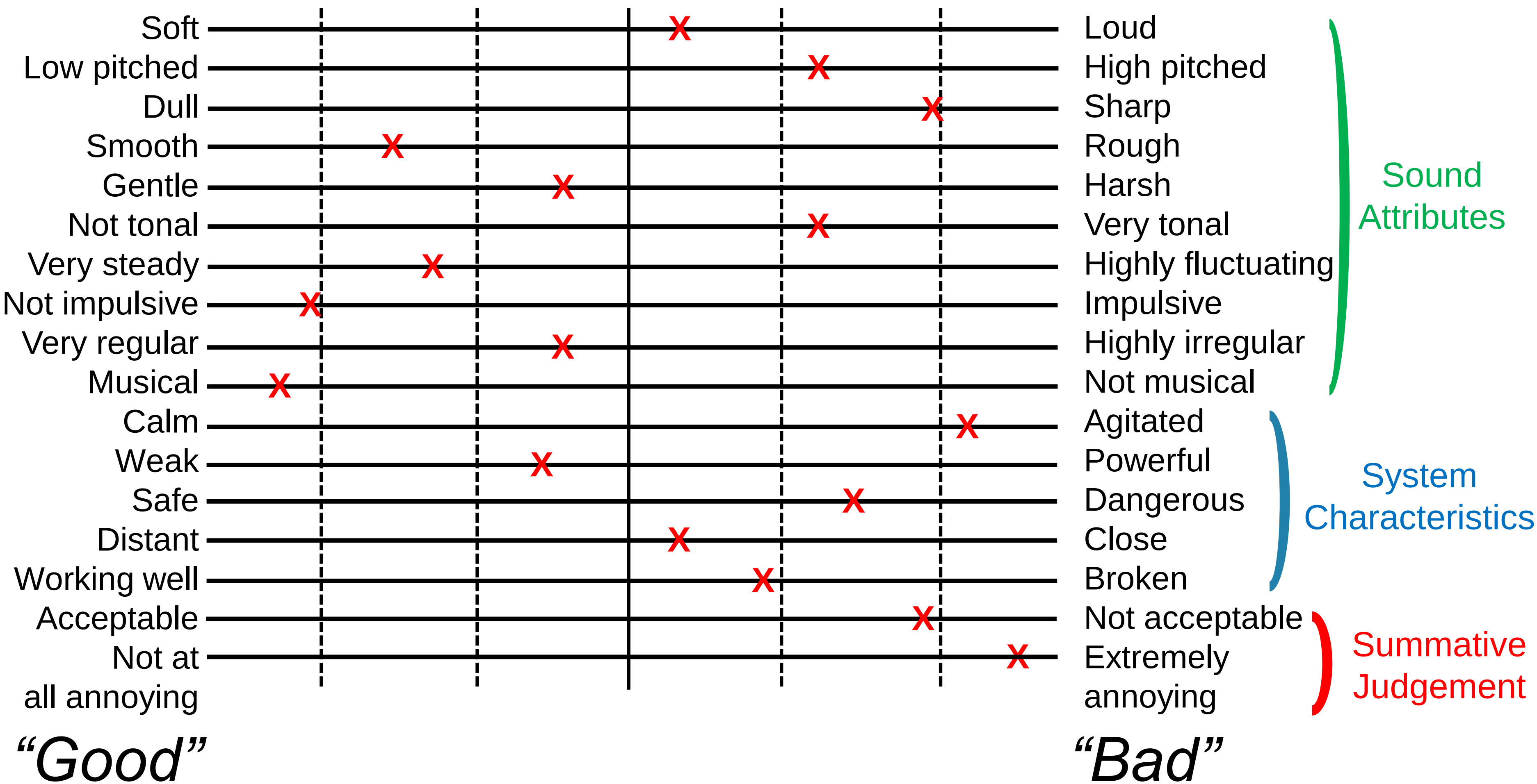
Classifications	Descriptor (number of times used)
Soft / Loud	Soft (56), Quiet (29), Muffled (16), Mild (10), Faint (7), Gentle (3) Medium (19), Moderate (17) Loud (210), Powerful (11), Intense (9), Strong (5), Vigorous (2), Not Soft (3)
Not Tonal / Tonal	Low (252), Low Frequency (12) Medium Frequency (10) High Pitch (54), Hum (43), High Frequency (17), High (17), Heavy (6), Prominent (3)
Dull / Sharp	Dull (3) / Metallic (21), Scratching (14), Sawing (12), Sharp (11), Squeal (6)
S[illegible] F[illegible]	[illegible]
Flu[illegible]	[illegible] 2) /
Impulsiveness	Drill (42), Choppy (25), Rattle (16), Repetitive (12), Drumming (6), Thudding (6), Thumping (4)
Pleasant / Annoying	Pleasant (4), Not Irritating (7), Not Annoying (3) / Annoying (86), Irritating (26), Noisy (19), Disturbing (18)
Emotional Response	Calm (16), Relaxing (5) / Hurt Ears (12), Scary (6), Headache (5), Painful (4)
Functionality	Safe (7), Efficient (4), High Performance (3), Properly Working / Old (15), Broken (4), Rusty (4), Ineffective (3), Dangerous (3), Unsafe (2)

- People noticed many different sound characteristics in addition to loudness
- Descriptions were consistent with annoyance ratings

- Part B – Rate the sounds (24 sounds)

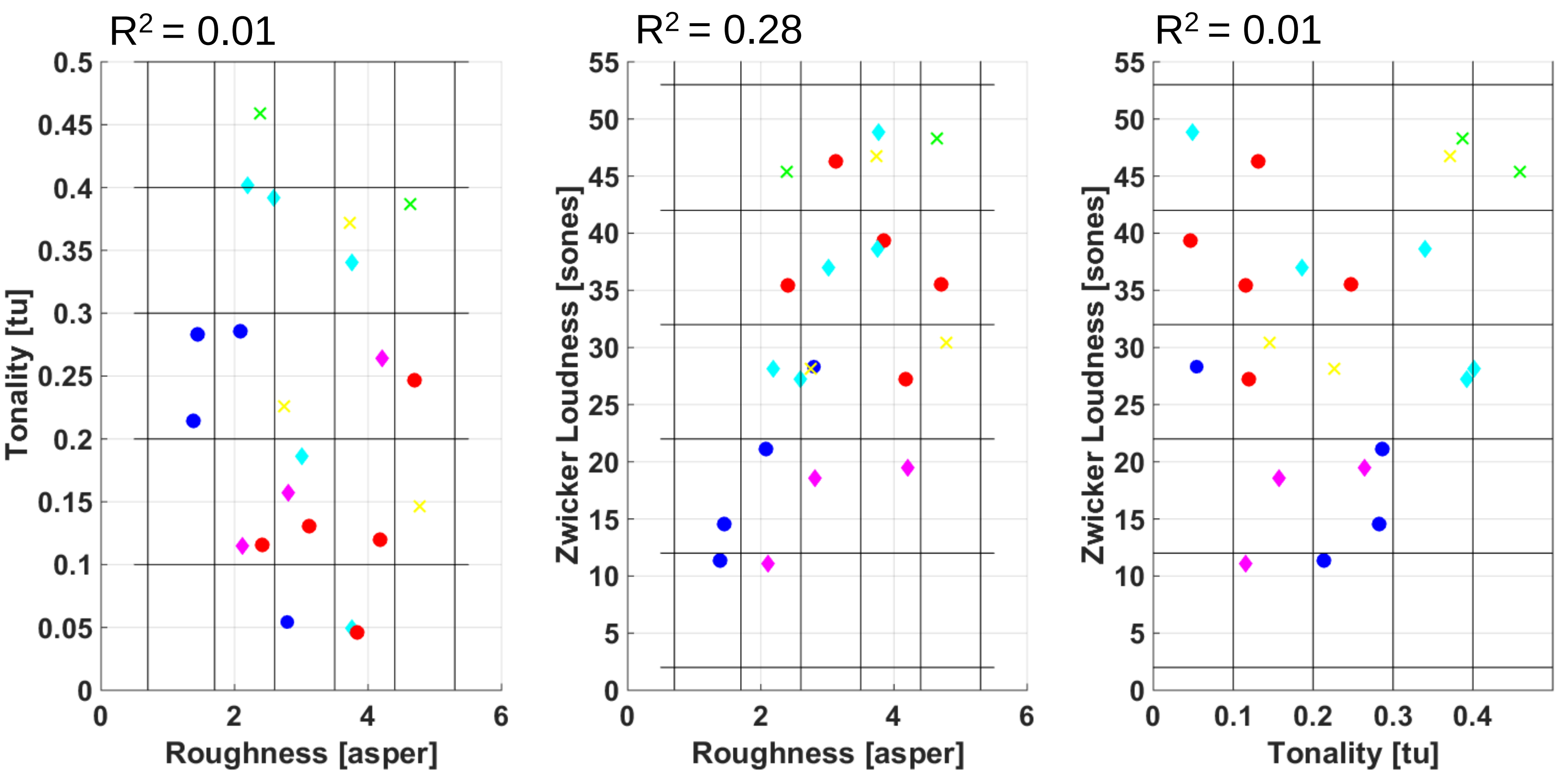


Proposed Semantic Differential Scales



Test Sounds Selection

- Total 22 sounds - 11 residential units, 11 mobile truck units
  - 9 original recordings, 13 modified recording



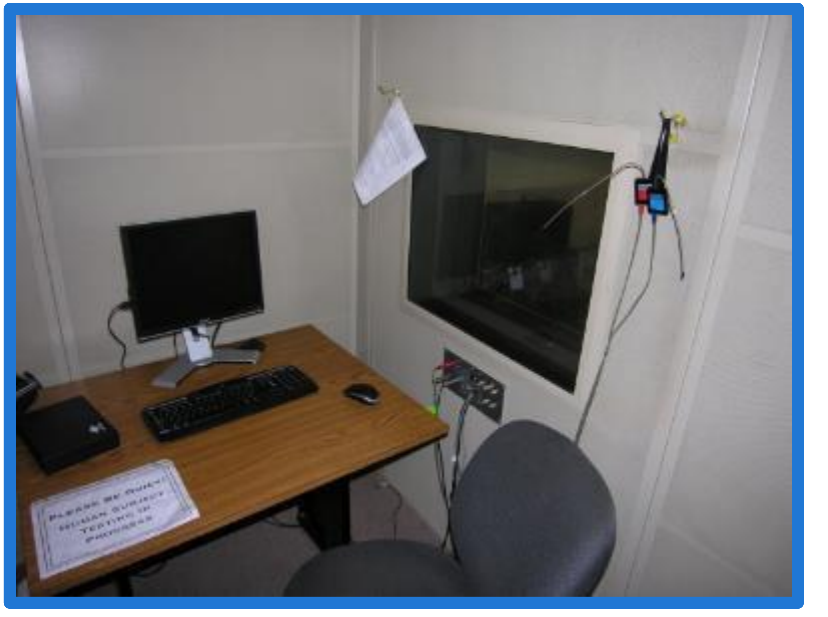
- Most metrics were calculated using Head ArtemiS software

Test Facility

- The test was performed in a Sound Quality Booth at Purdue University

- Sounds were played back through a high quality LynxOne sound card, Tucker-Davis HB7 amplifier, and a set of Etymotic Research ER-2 tube earphones

- Disposable foam eartips (ER-14A) were used with earphones



Test Procedure

- Overview of the test
- Consent form (Purdue IRB # 1507016324) & Questionnaire
- Hearing Test

- Dictionary definition (if needed)
- Listen to sounds for familiarization (10 sounds)
- Test Scenario
- Practice Test (2 sounds)
- **MAIN SEMANTIC DIFFERENTIAL TEST**

- Comments
- Repeat Hearing Test
- Payment

Approx.
1 hour

Subjects & Demographics

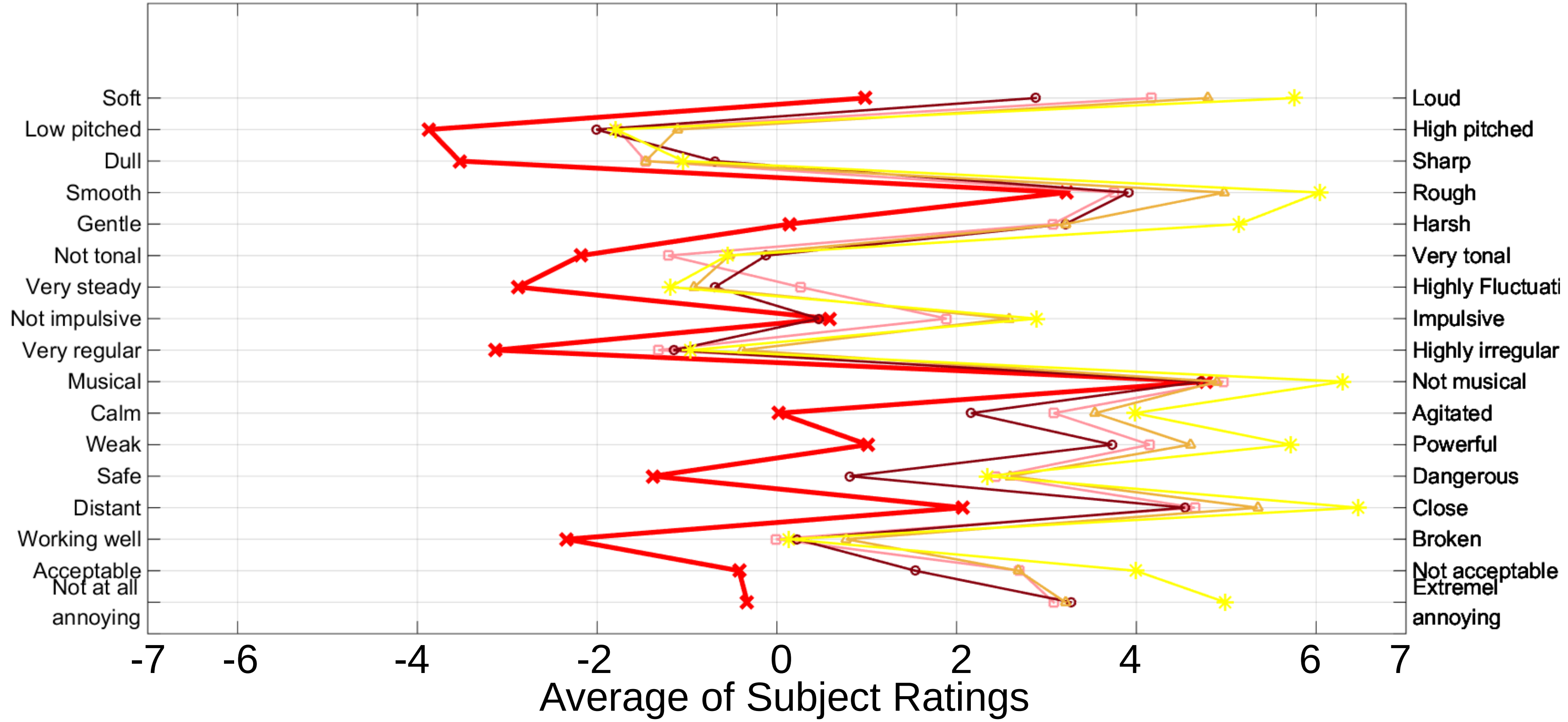
- Total Number of Subjects: 39
- Average Age: 27.2 (19 – 51), median Age: 24

Male	Female
22	17

Caucasian	Asian	Hispanic
21	15 (7 China, 5 South Korea, 3 India)	3 (1 Peru, 1 Mexico, 1 Argentina)

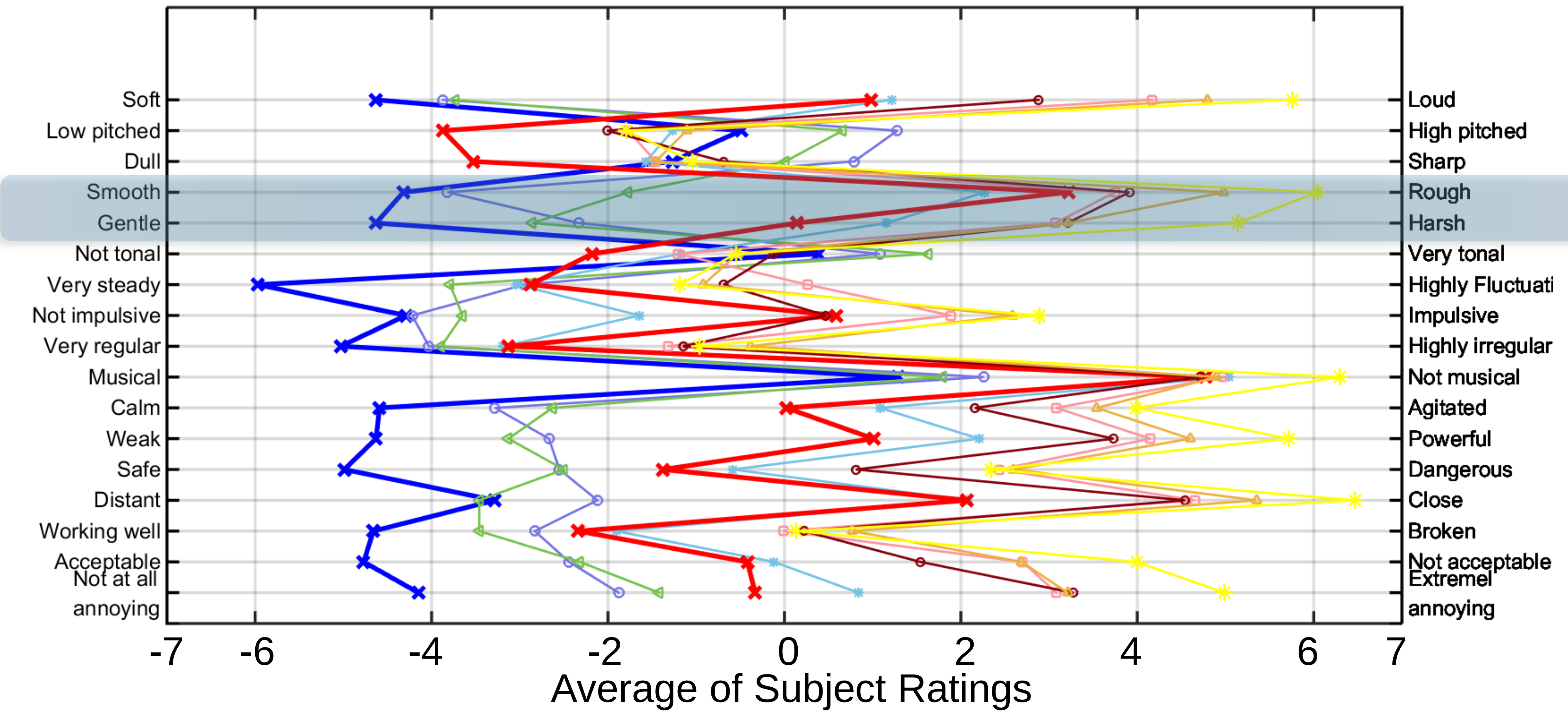
- Students, staffs at Purdue University & West Lafayette Community

Test Results – Average Scale Ratings for Mobile Truck Recordings



YELLOW→RED: Mobile Truck

Test Results – Average Scale Ratings for the 9 Recordings



BLUE→GREEN: Residential YELLOW→RED: Mobile Truck

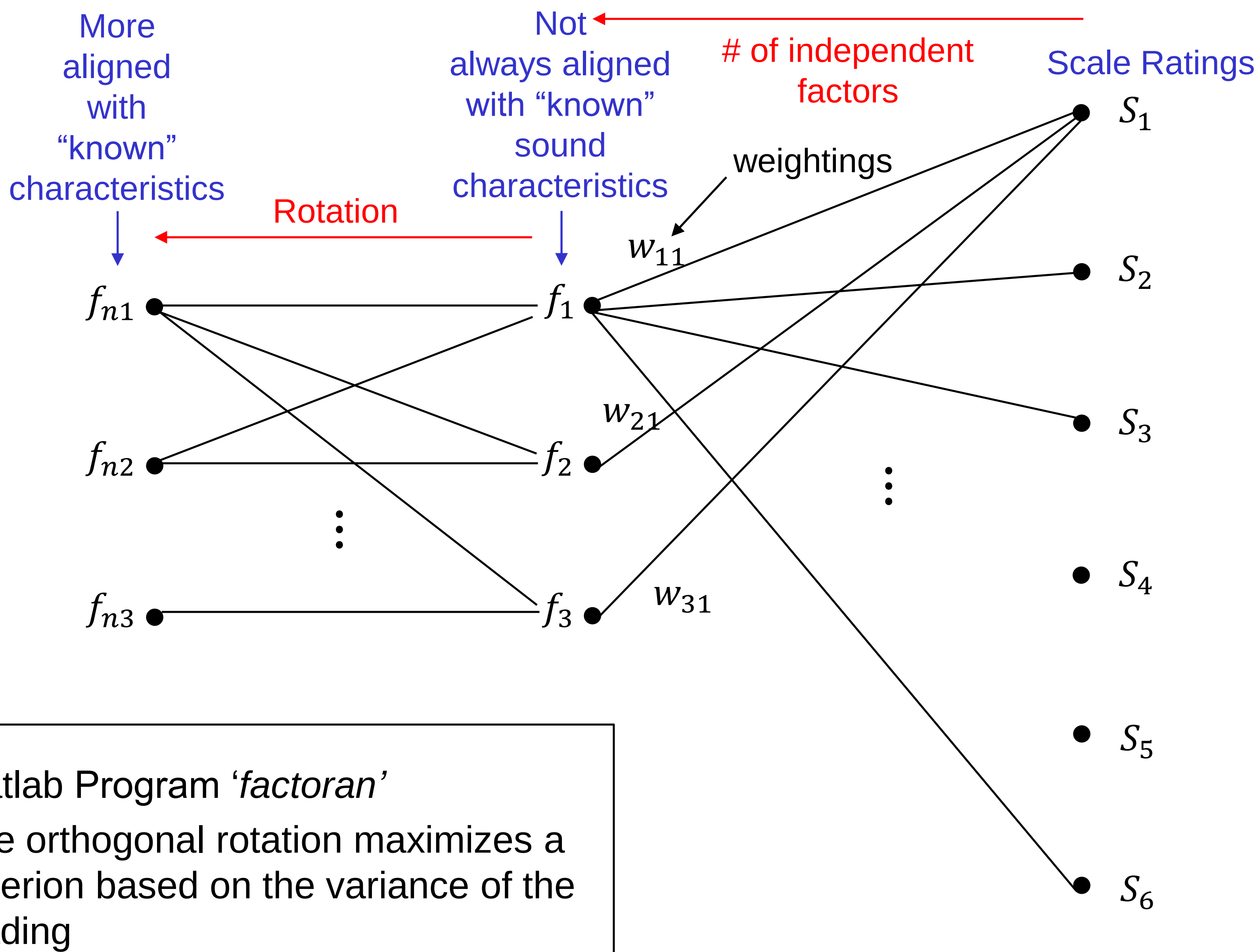
- Two strong patterns (thick blue and thick red lines)
- Profile shapes of same type of units are similar, but not always

Test Results – Sound Quality Metrics and Ratings

Word Scale	Correlation Coefficient(ρ)								
	N_5	SQI*	dB(A)	Rough -ness (R_5)	Tonality (DIN)	Aures' Tonality	Fluctuation Strength	Sharpness	
								S_{VBS}	S_{AS}
Soft – Loud	0.95	0.96	0.97	0.57	0.16	-0.21	0.24	0.20	0.79
Low pitched – High pitched	0.34	0.45	0.37	-0.14	0.69	0.55	-0.02	0.82	0.74
Dull – Sharp	0.46	0.56	0.51	0.02	0.68	0.45	0.01	0.81	0.82
Smooth – Rough	0.81	0.75	0.84	0.79	-0.16	-0.54	0.26	-0.16	0.49
Gentle – Harsh	0.90	0.92	0.96	0.57	0.16	-0.24	0.20	0.27	0.82
Not tonal - Very tonal	0.21	0.29	0.15	-0.26	0.77	0.79	-0.06	0.62	0.49
Very steady – Highly fluctuating	0.62	0.61	0.64	0.50	0.10	-0.21	0.37	0.12	0.52
Not impulsive – Impulsive	0.72	0.70	0.74	0.69	-0.12	-0.42	0.32	-0.16	0.42
Very regular – Highly irregular	0.60	0.57	0.63	0.53	0.00	-0.29	0.36	0.10	0.51
Musical – Not musical	0.85	0.86	0.92	0.63	0.03	-0.38	0.09	0.12	0.68
Calm – Agitated	0.92	0.93	0.95	0.58	0.21	-0.17	0.21	0.24	0.80
Weak – Powerful	0.95	0.95	0.97	0.57	0.08	-0.29	0.26	0.12	0.74
Safe – Dangerous	0.91	0.91	0.91	0.47	0.30	-0.06	0.22	0.36	0.85
Distant – Close	0.94	0.97	0.97	0.54	0.16	-0.20	0.27	0.19	0.77
Working well – Broken	0.88	0.88	0.88	0.56	0.20	-0.10	0.34	0.24	0.76
Acceptable – Not acceptable	0.90	0.92	0.92	0.48	0.29	-0.06	0.19	0.37	0.86
Not at all annoying - Extremely annoying	0.91	0.93	0.93	0.49	0.30	-0.06	0.18	0.36	0.87

Relatively high correlation between sound quality metric and associated average word scale rating (subjects' perception)

Factor Analysis



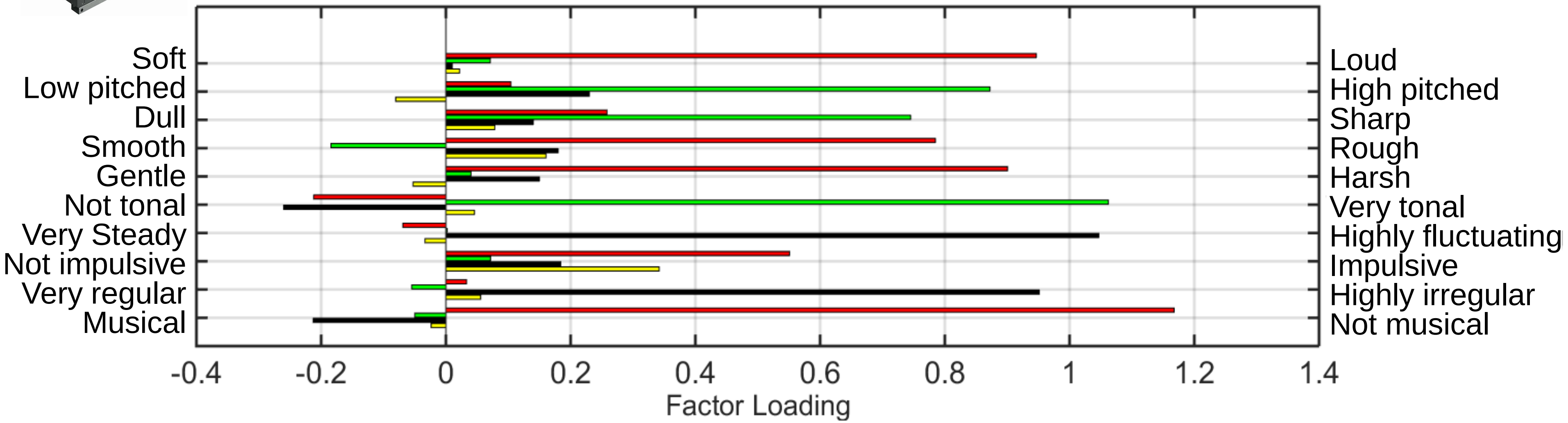
- Matlab Program '*factoran*'
- The orthogonal rotation maximizes a criterion based on the variance of the loading

Results of Several Factor Analysis

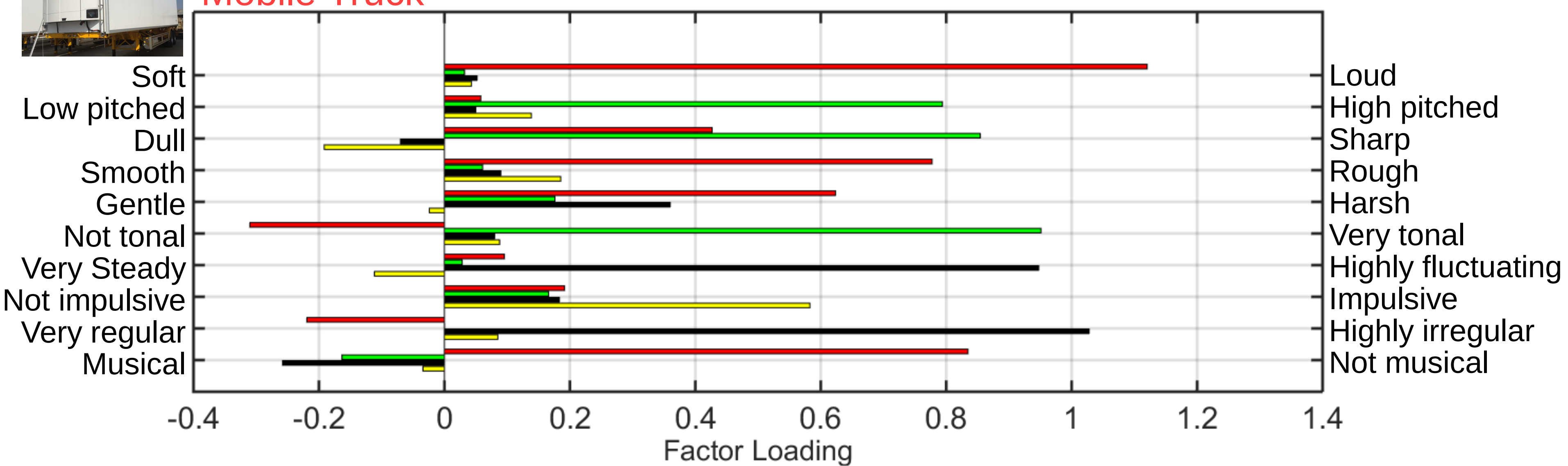
	SIGNALS	SCALES
1.	Mobile Truck Sounds	Sound Attributes
2.	Residential Sounds	Sound Attributes
3.	All	Sound Attributes
4.	All	All

Four Factor Analysis on Sound Attribute Scales - by Unit

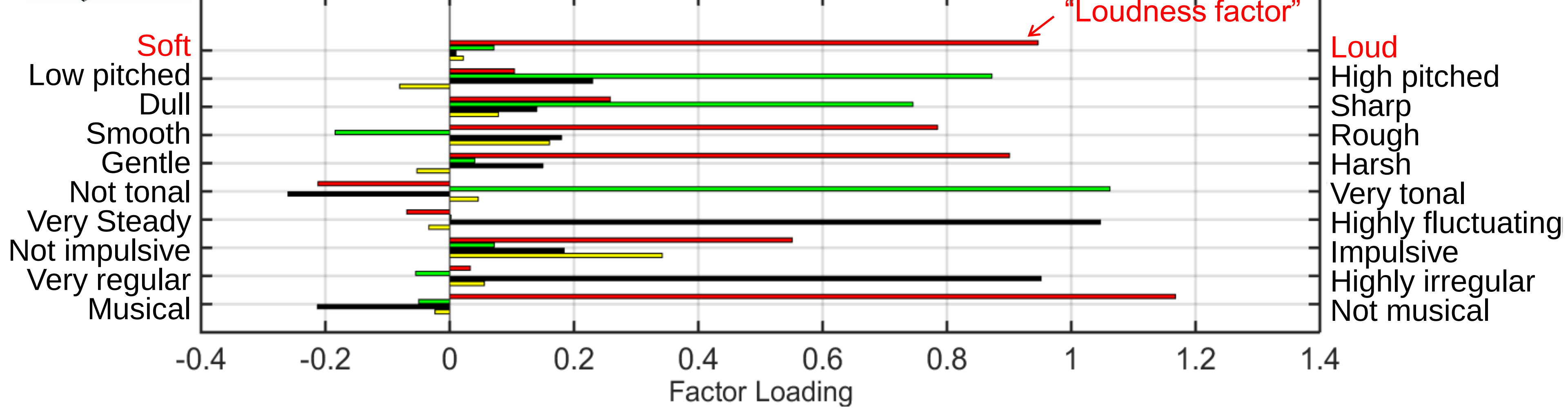
Residential

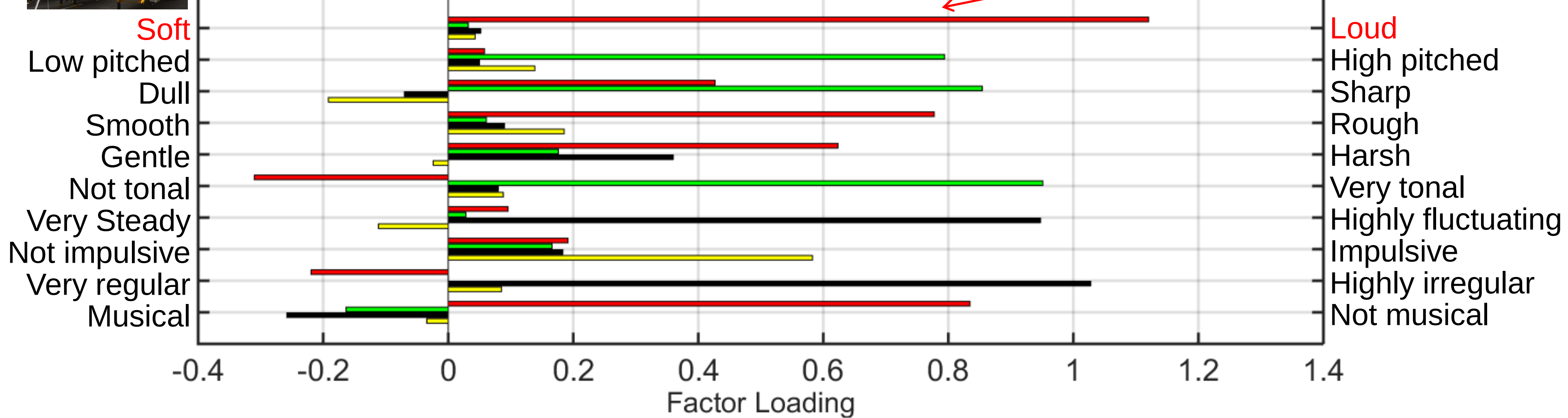


Mobile Truck

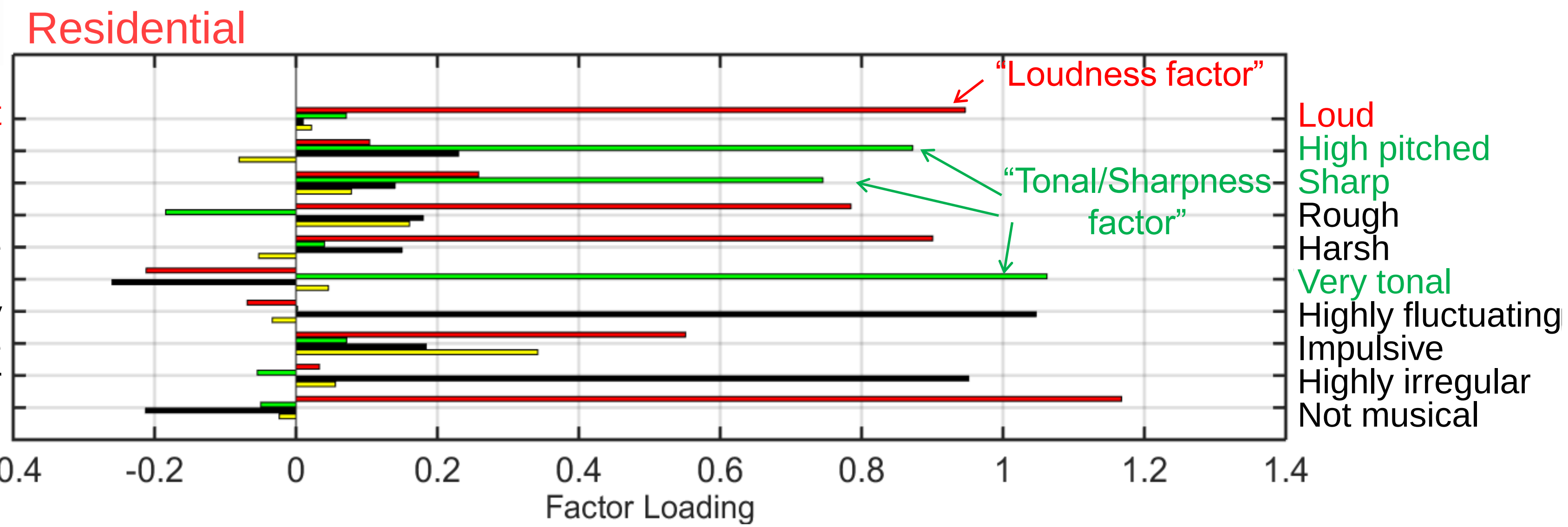


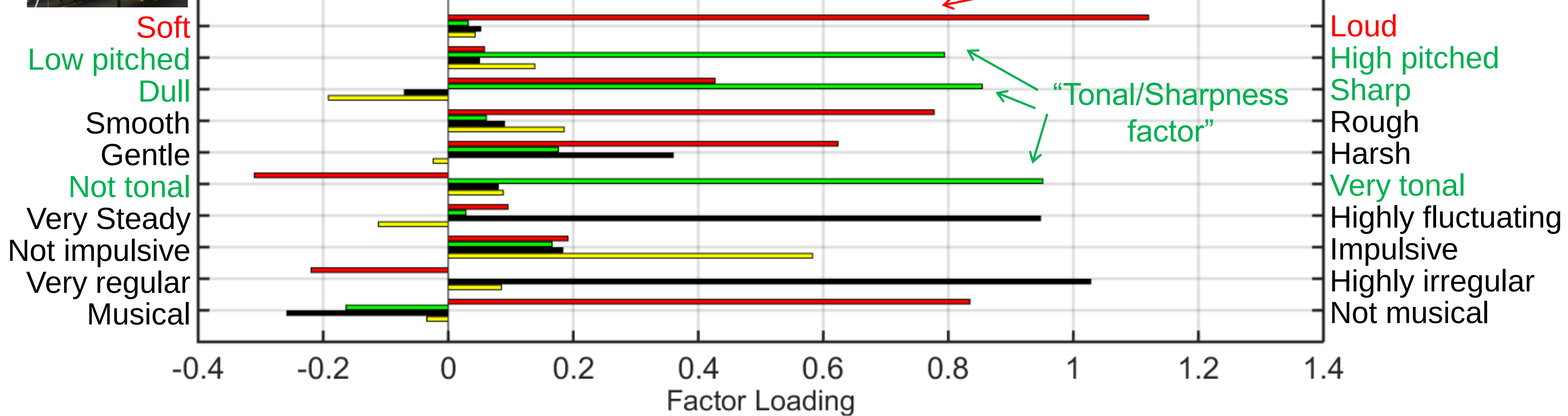
Four Factor Analysis on Sound Attribute Scales - by Unit

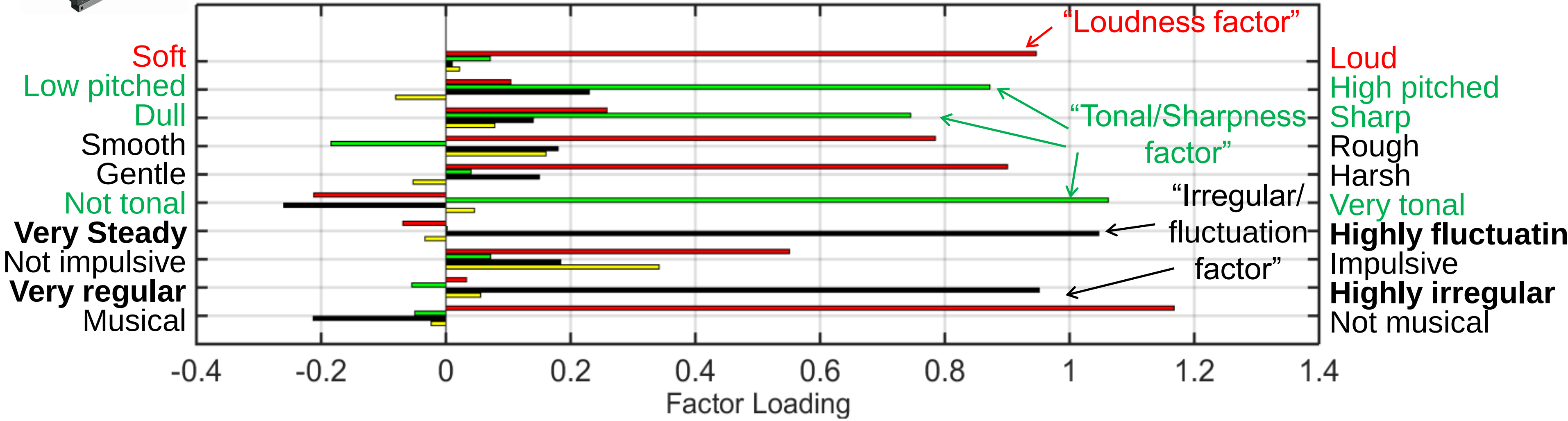
Four Factor Analysis on Sound Attribute Scales - by Unit



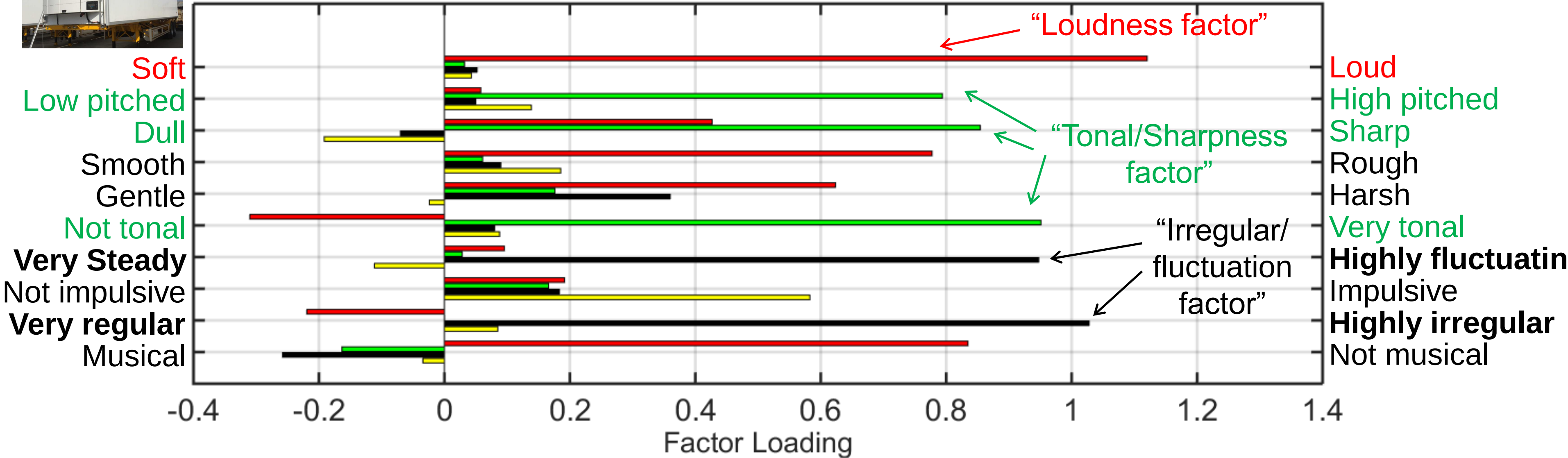


Four Factor Analysis on Sound Attribute Scales - by Unit

Residential

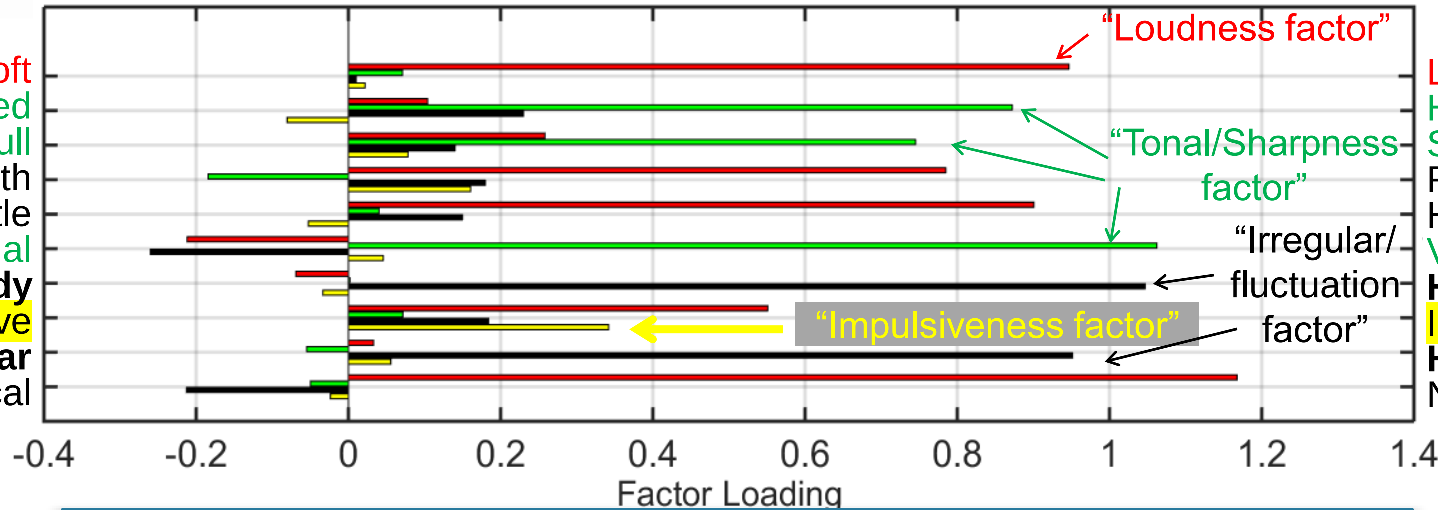


Mobile Truck



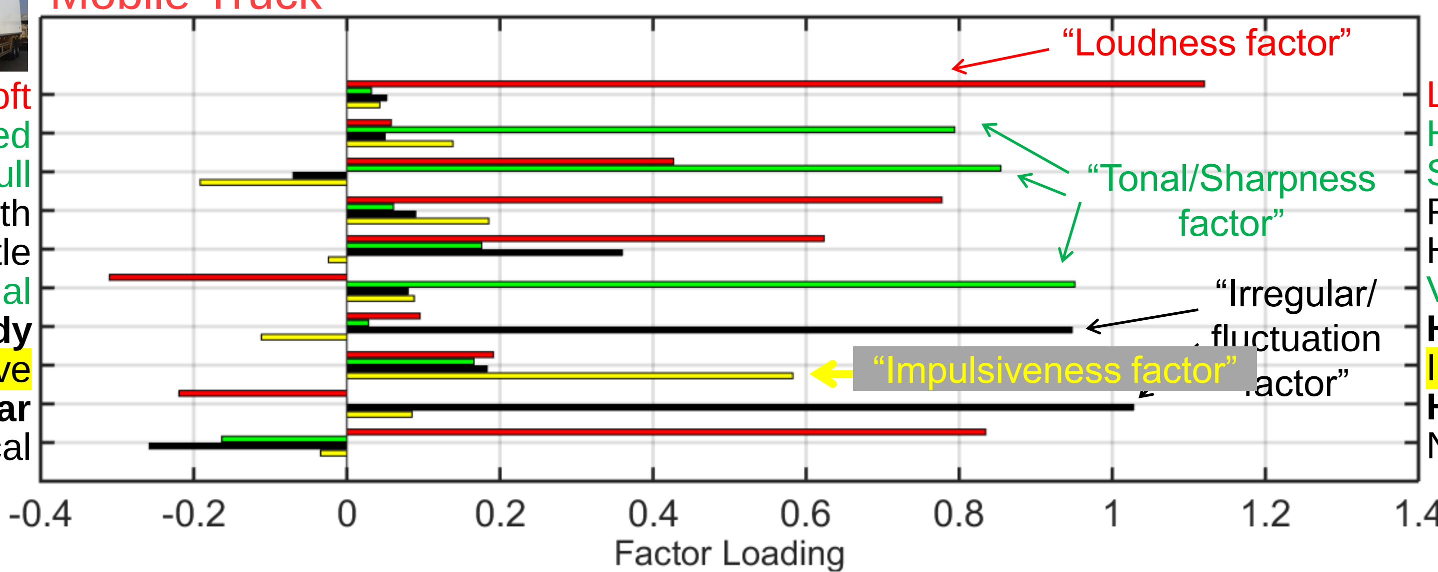
Four Factor Analysis on Sound Attribute Scales - by Unit

Residential

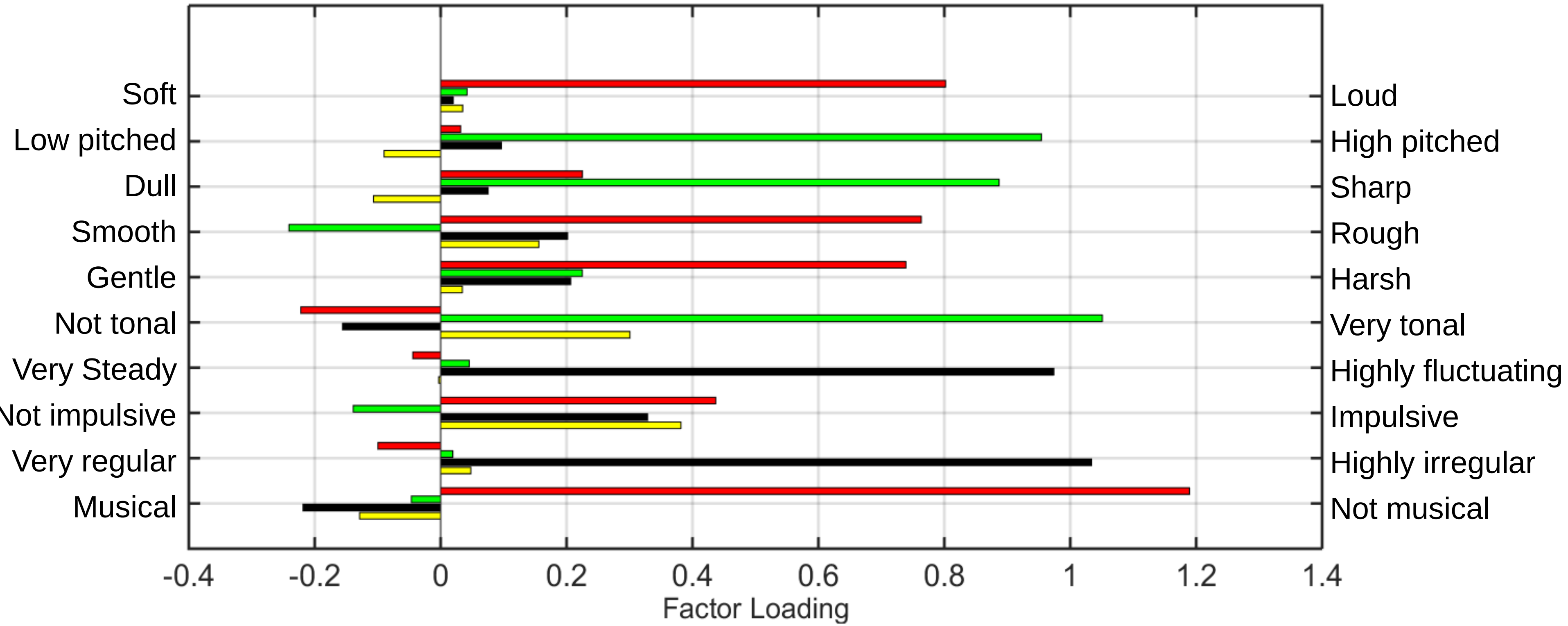


Higher "Impulsiveness" factor loading in truck unit

Mobile Truck



Four Factor Analysis on Sound Attribute Scales - ALL Unit



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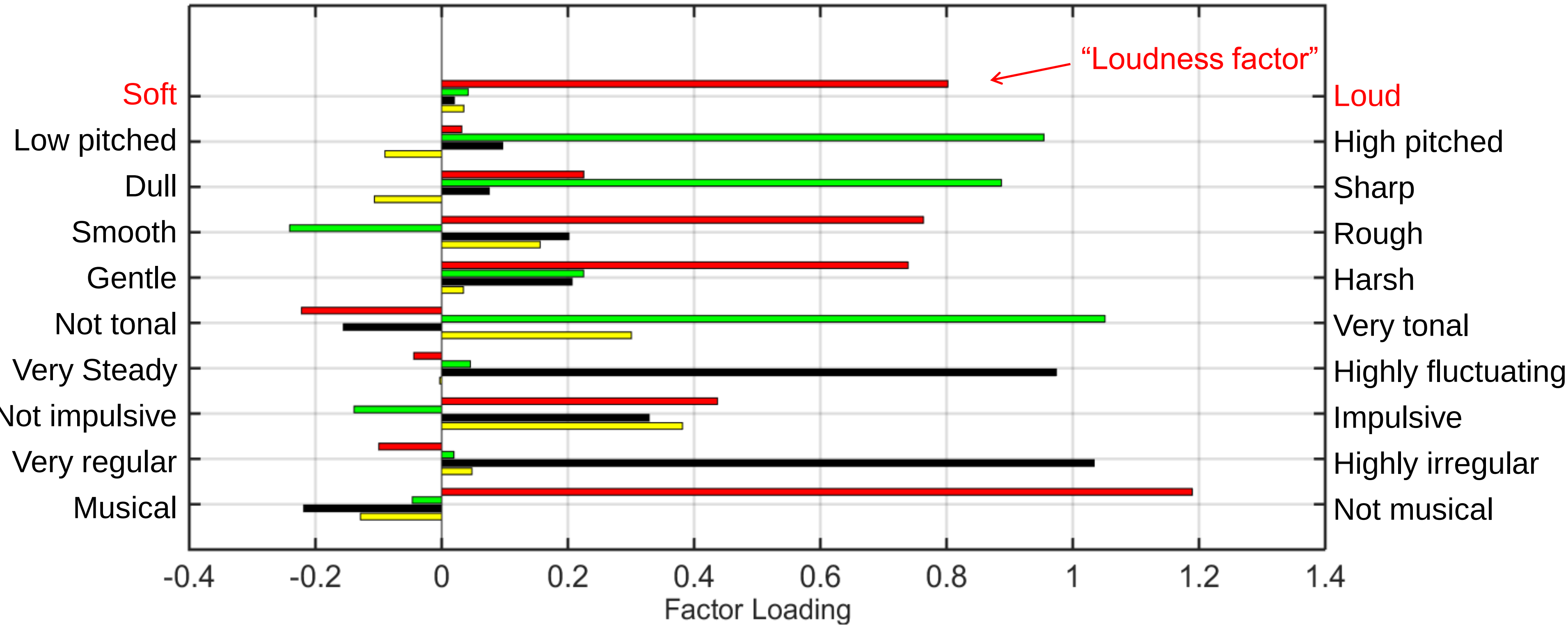
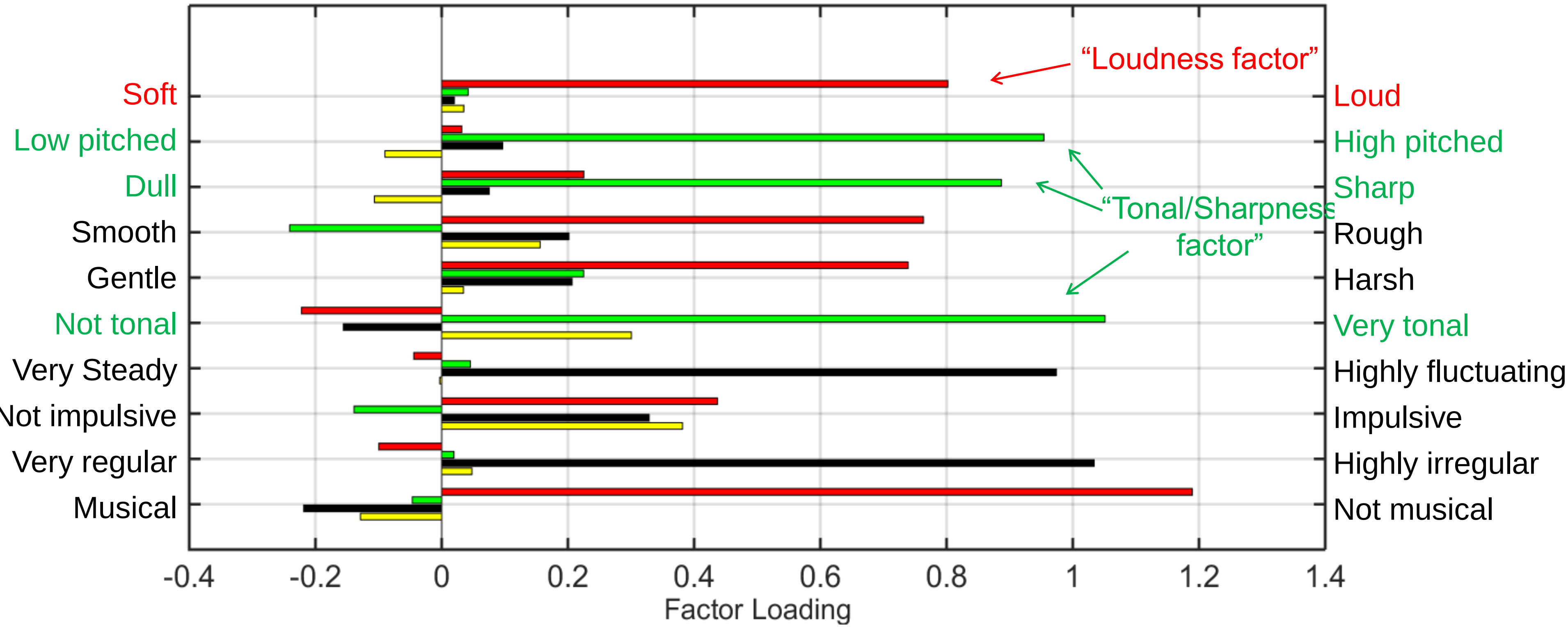


Four Factor Analysis on Sound Attribute Scales - ALL Unit



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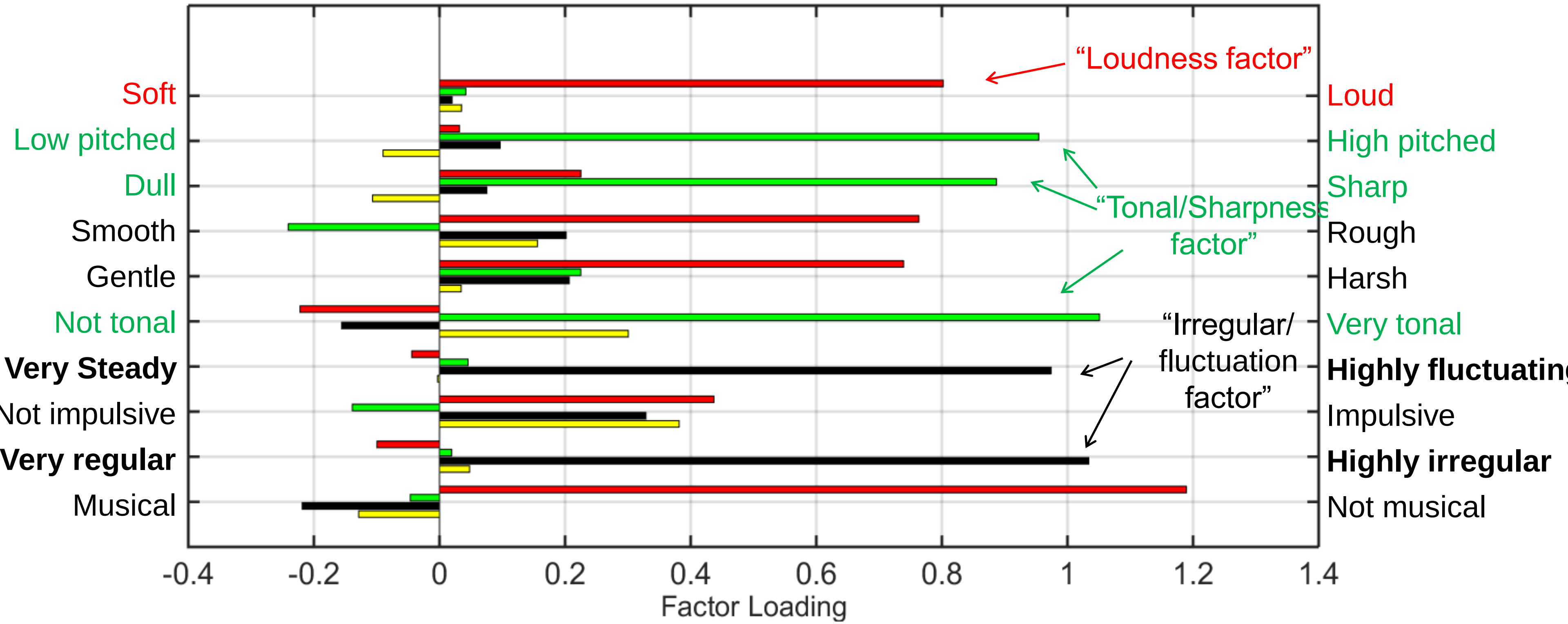
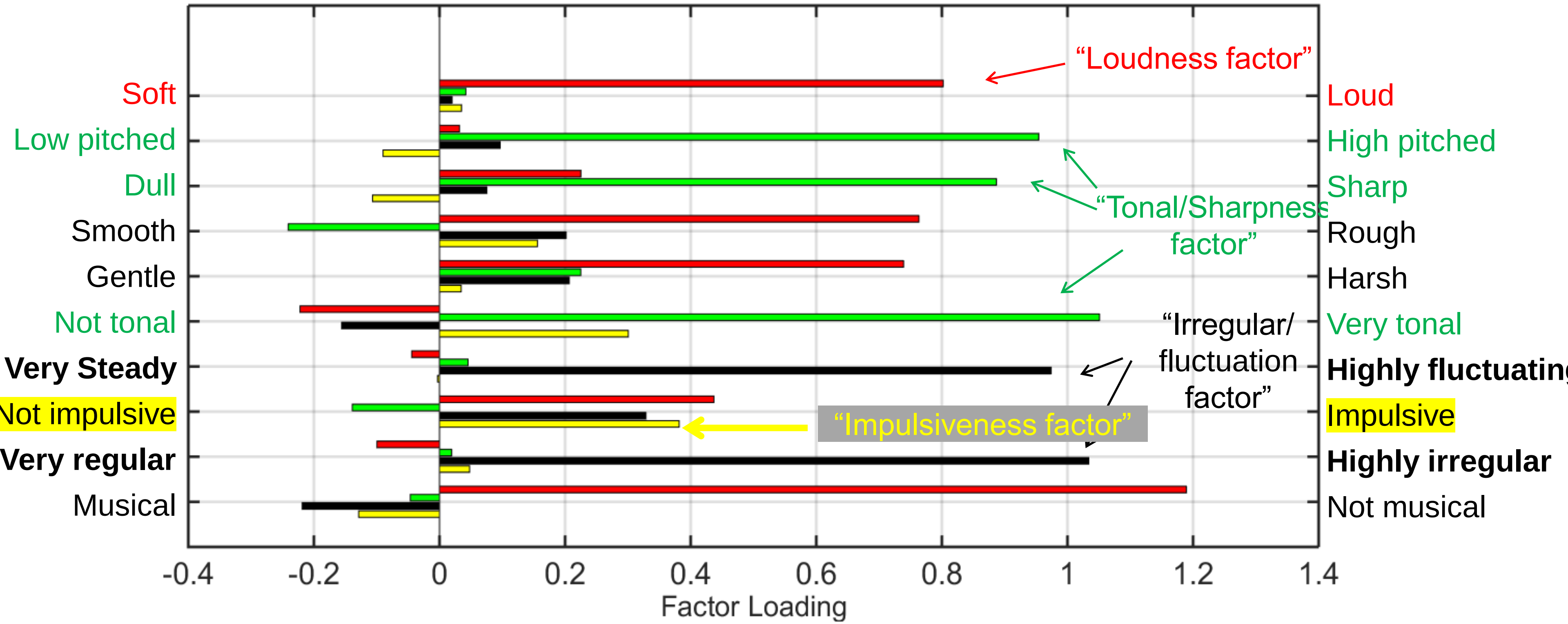
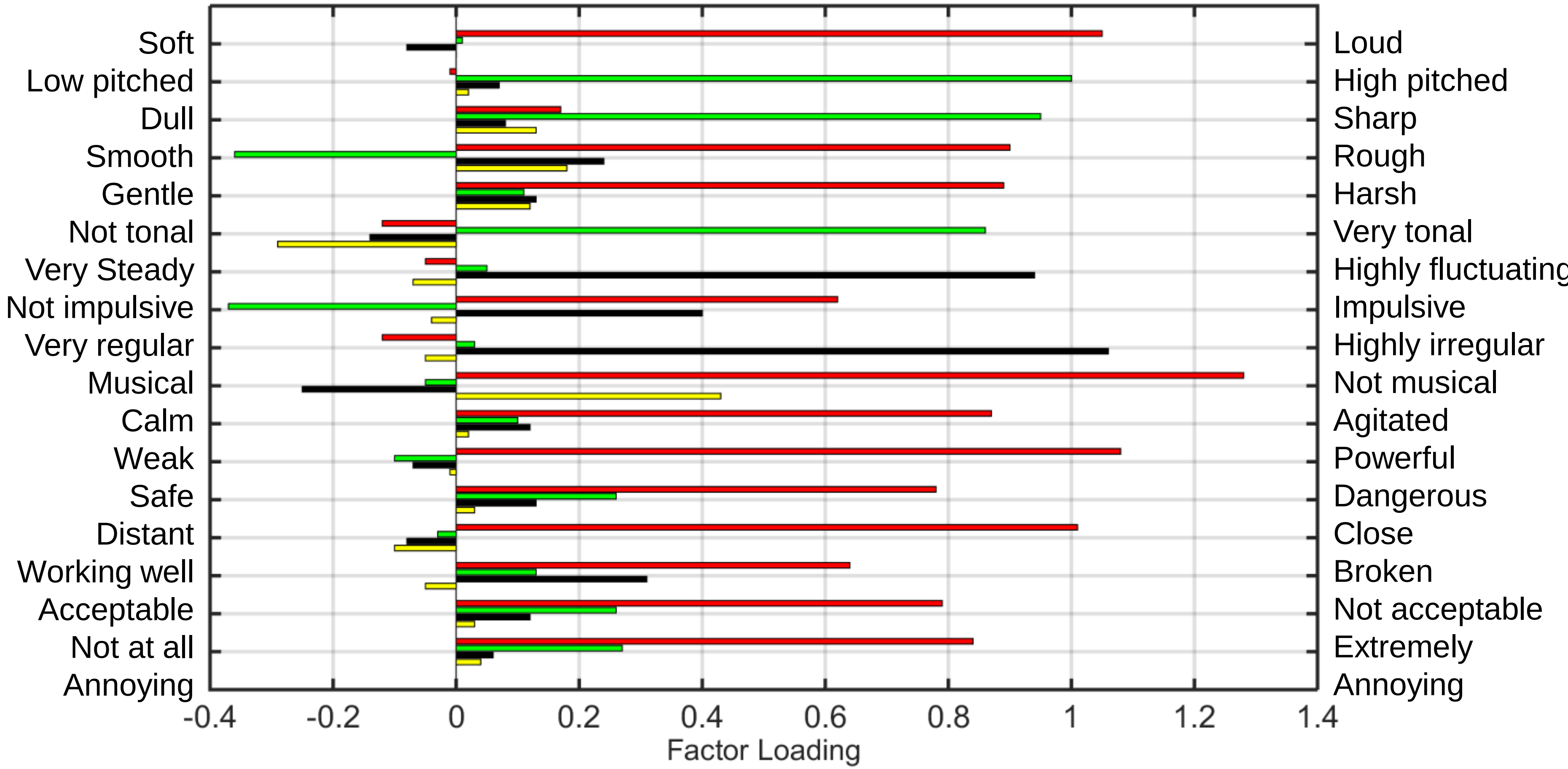


Four Factor Analysis on Sound Attribute Scales - ALL Unit

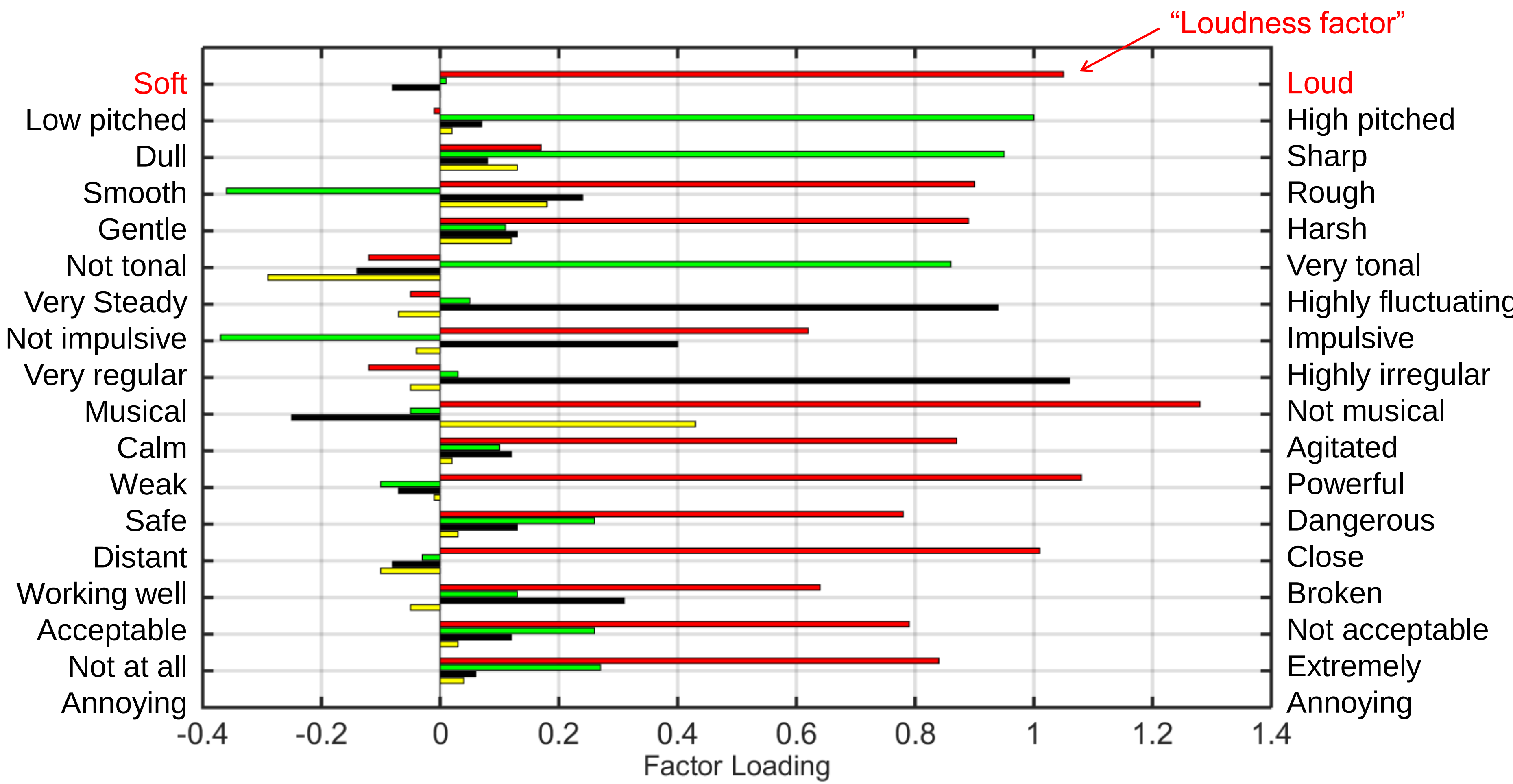


- Same first three factors
- Weaker "Impulsiveness factor"

Four Factor Analysis – All Units
Weightings of Factor on Each Scale



Four Factor Analysis – All Units
Weightings of Factor on Each Scale



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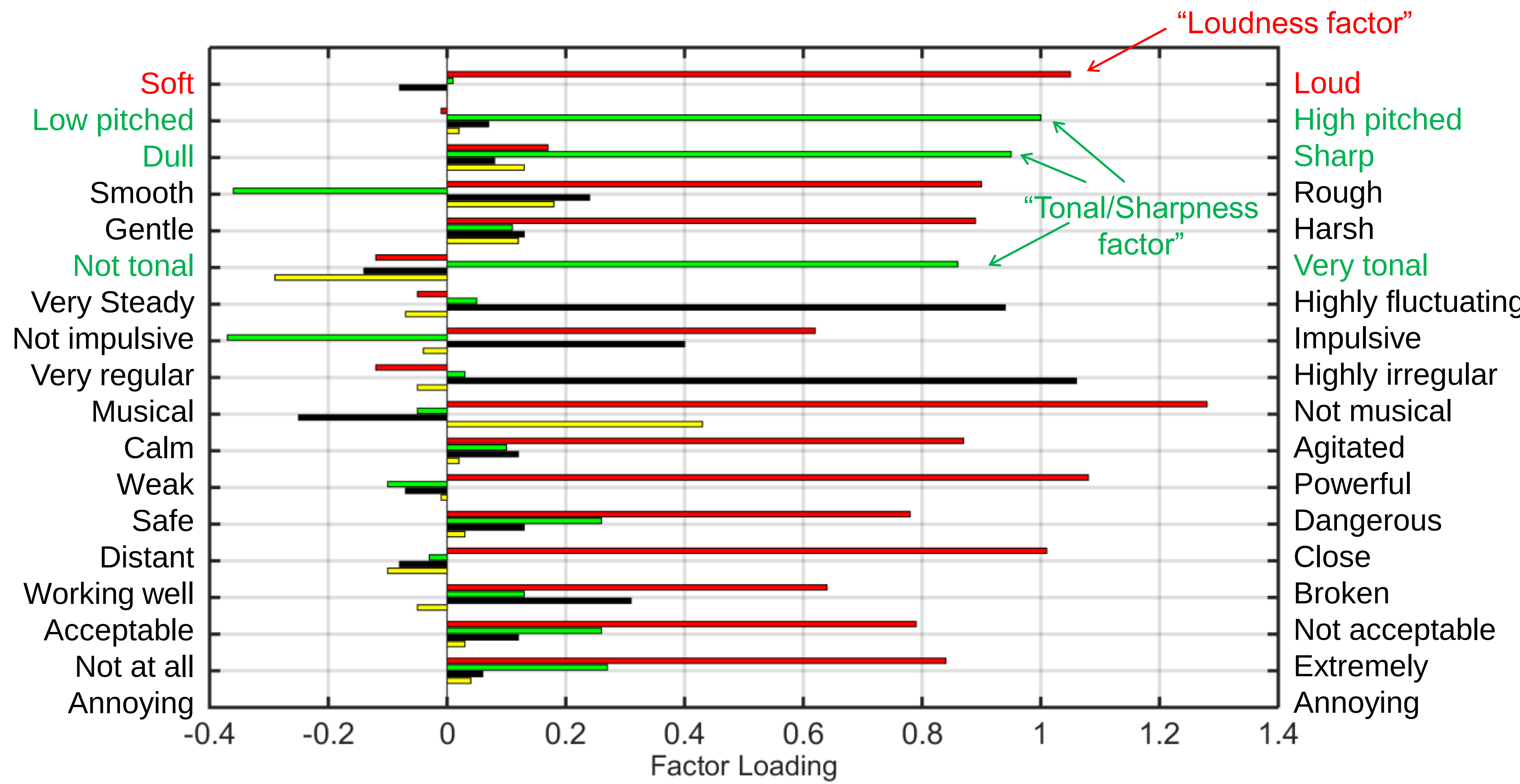
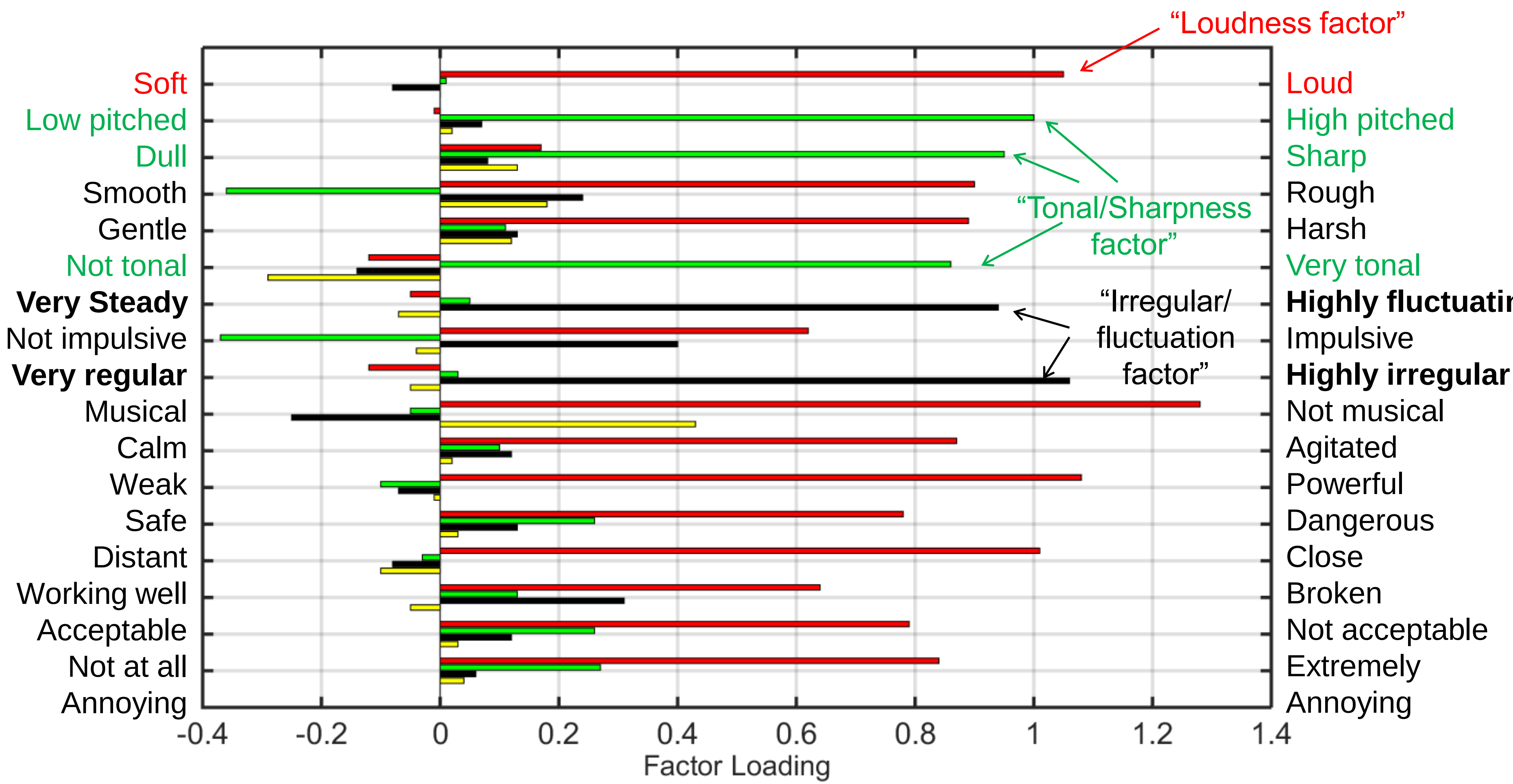
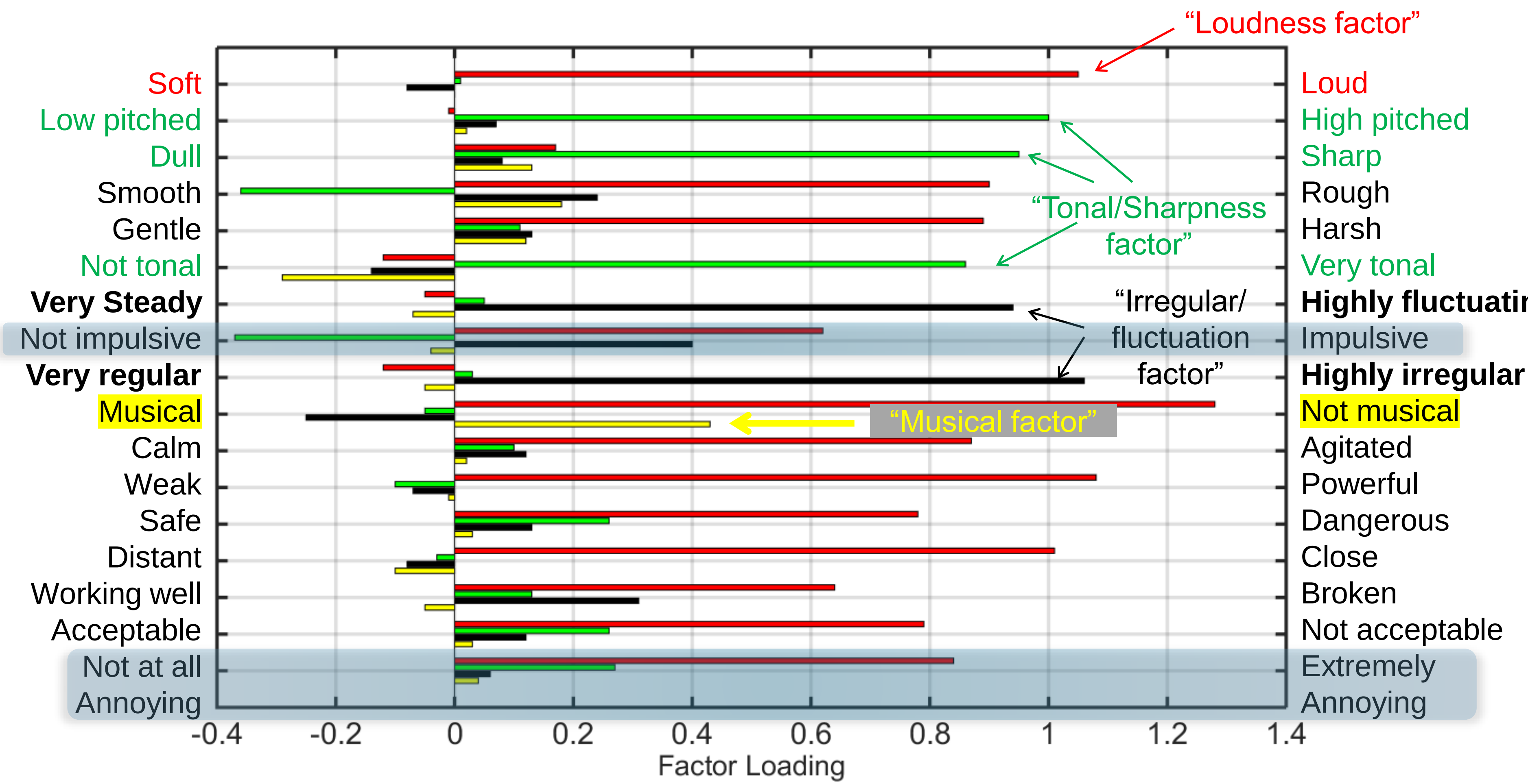
Weightings of Factor on Each Scale



Four Factor Analysis – All Units
Weightings of Factor on Each Scale

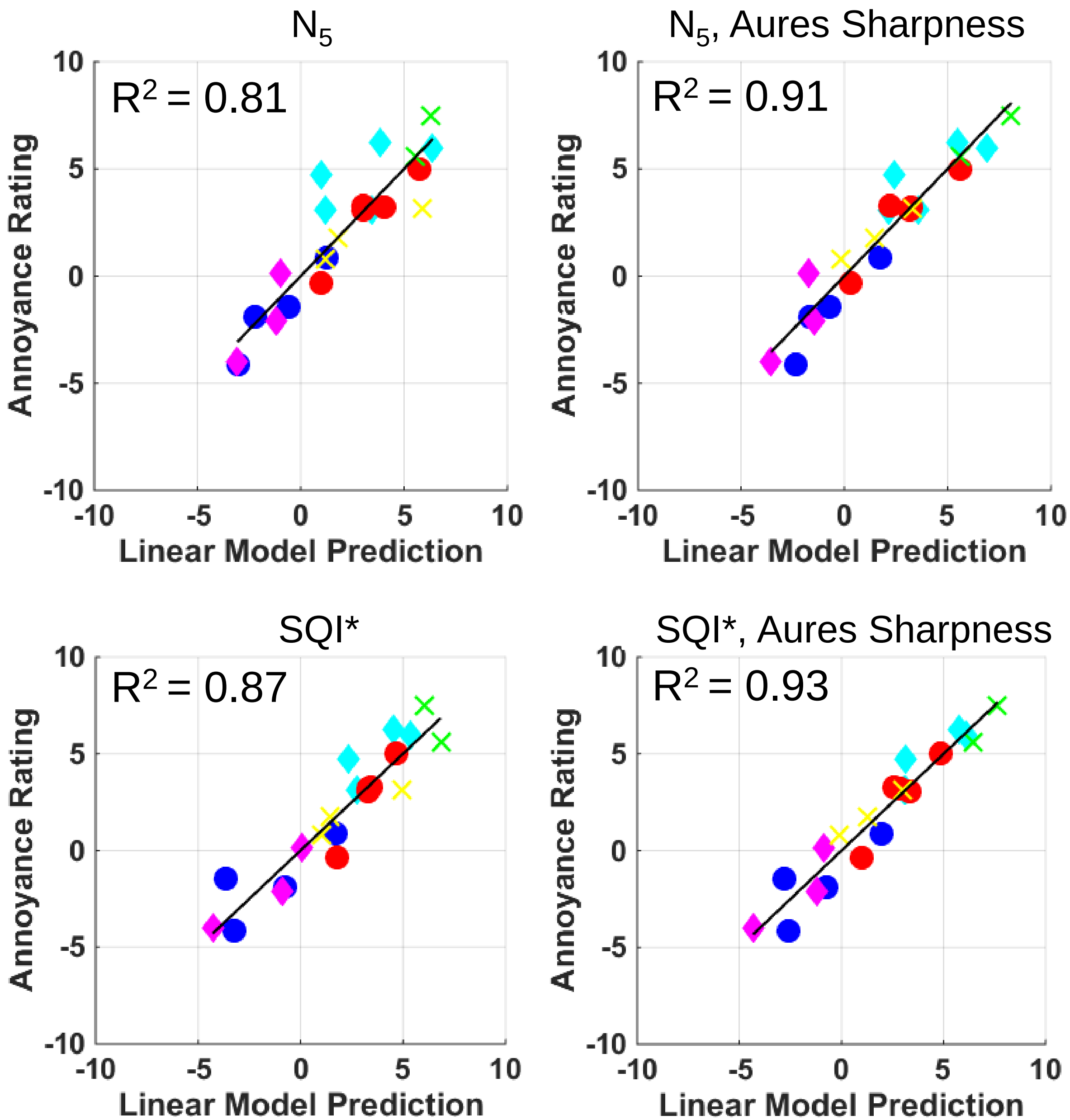


Four Factor Analysis – All Units
Weightings of Factor on Each Scale



- Tonal and Sharpness factors are always combined → Need separation
- Annoyance scale were strongest for the "Loudness" and "Tonal/Sharpness" factor
- Impulsive sounds are loud, irregular and not sharp/tonal

Annoyance Models' Prediction



- Aures Sharpness metric significantly increases the accuracy of annoyance prediction
  - In line with the result of the factor analysis
- Adding Tonality metric (DIN) does not increase R^2 value

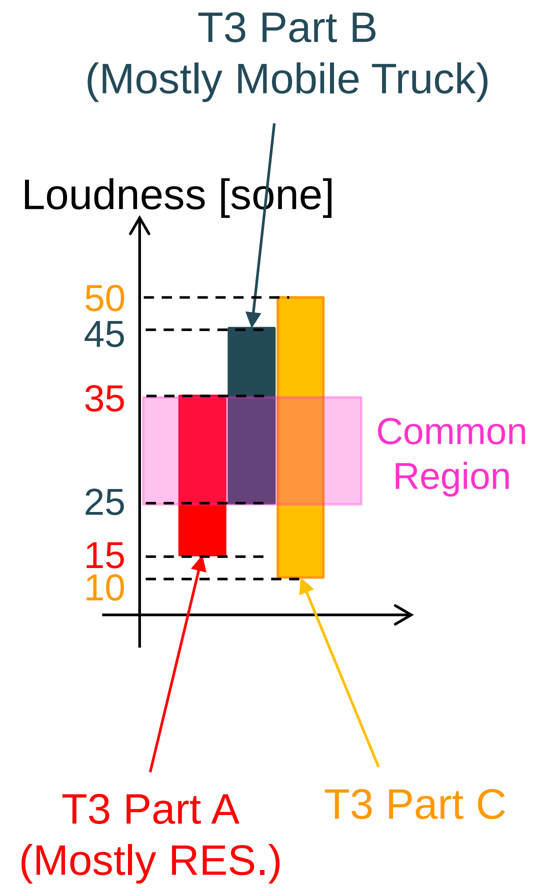
Conclusions

- Two strong patterns were found in average rating profiles associated with machine type
- Sound quality metrics and scale ratings aligned well
- The strong factors: “Loudness”, “Tonal/Sharpness”, and “Irregular/Fluctuation”
- SQI* (tone corrected loudness) was the metric most highly correlated with average annoyance ratings
- The best two-metric models for predicting annoyance include SQI* and Aures Sharpness

  → Consistent with the result of the factor analysis

Future Work

- More signal modification techniques
  - Modify sharpness and tonality independently
- Only 22 sounds in Test 2
  - Design Test 3
    - Three sets of rating tests (organized by range of loudness)
    - 150 Test Sounds
      - Part A: 50 sounds, mostly Residential
      - Part B: 50 sounds, mostly Mobile Truck
      - Part C: 50 sounds, all units



Thank you!

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Sound Quality Indicator (SQI, SQI*)

- AHRI calculation procedure is the preferred method of assessing the quality of sound for Air-conditioning and refrigeration equipment

Example Calculation of AHRI Sound Quality Indicator (SQI)					
One-third Octave Band Center Frequency, Hz	Un-Weighted Unit Sound Power Level Lw, dB	Band Projection, dB	Tone Adjustment, dB	Un-weighted Unit Sound Power Level Plus Tone Adjustment Lw, dB	Rating Indices
100	84.5			84.5	2.7
125	91.5	5	-0.7	90.8	4.9
160	88.5			88.5	4.8
200	84.5			84.5	4.2
250	82			82	3.7
315	83	2	1.2	84.2	4.7
400	80			80	4

Test Sounds: Modified Recordings