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Descriptors of Sound from HVAC&R Equipment

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Acknowledgement

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  - Jelena Paripovic and Daniel Carr

Introduction

- HVAC&R equipment noise can be annoying

- Possible Noise induced sleep problems
  - e.g. ref. Passchier-Vermeer & Passchier, 2000

http://www.carrier.com/performance-parts/en/worldwide/

- HVAC&R noise can have a negative effect on work efficiency
  - e.g. ref. Holmberg, 1997

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 (Susina *et al.,* 2004)
  (Susini *et al.,* 2004; Schneider and Feldmann, 2015; Naji and Sanan, 2015)

Compressor

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

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

Overview of the Subjective Tests

Signal Modification
Loudness, sharpness, roughness, and tonality

Test 1
a. Description Test
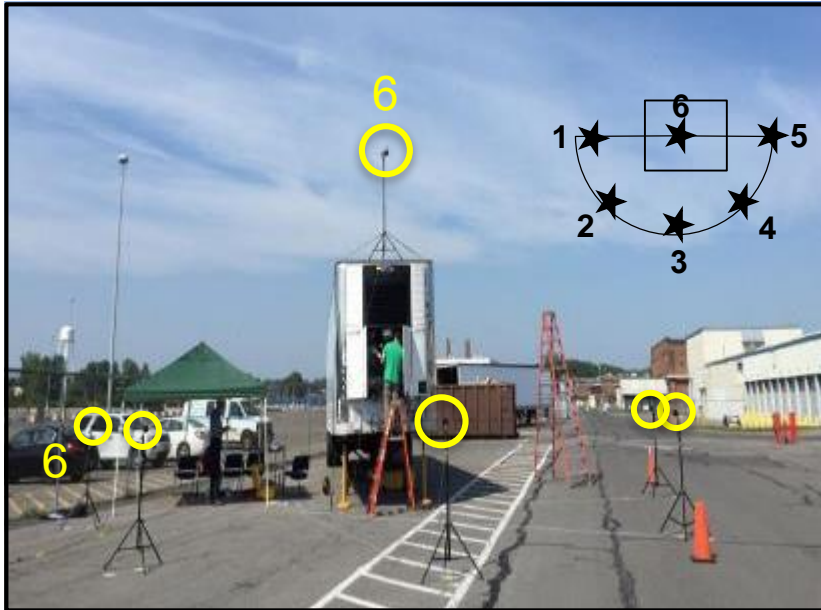b. Rating Test

Test 2
Semantic Differential Test

Test 3
Rating Test

Focus:
- Classification of descriptors
  → Semantic scale development
- Preliminary annoyance model

Test Sounds: Original Recordings

- Refrigeration truck unit
  - Two measurement standards (ANSI, TNO)
  - 7 or 7.5m from unit (MIC 1-5)
  - 6 MICs

- Residential unit
  - 1.5m from unit
  - 1 MIC

Test Sounds: Modified Recordings, Why?

- If two metrics are always highly correlated in an application, we only need to use one of these metrics in our sound quality model
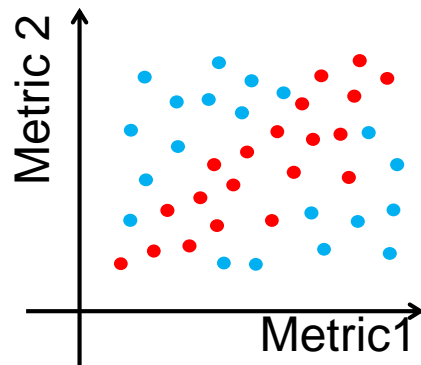
If both metrics are important?
→ Modify signals to de-correlate metrics (fill in gaps)

Test Sounds: Modified Recordings

Original Recording

Filters

Increased Sharpness

Reduced Sharpness

Increased Roughness

Increased Tonality

Decreased Tonality
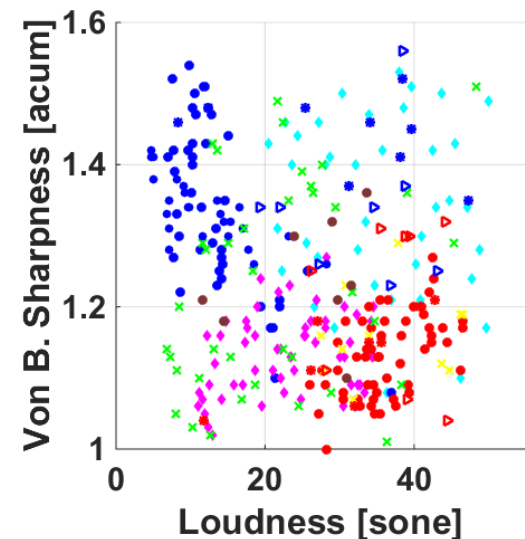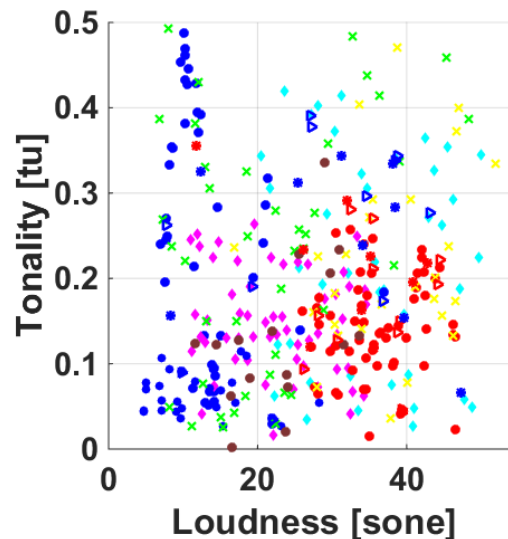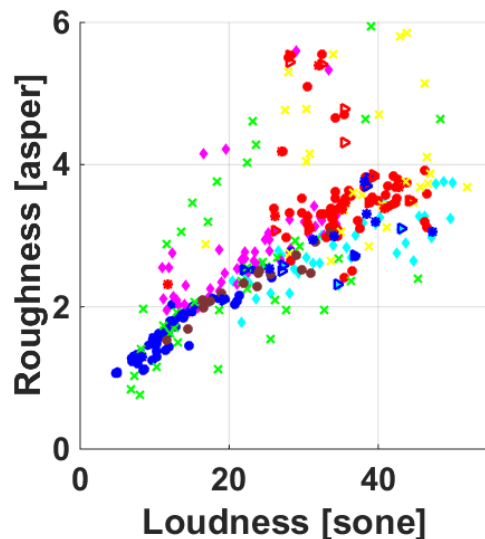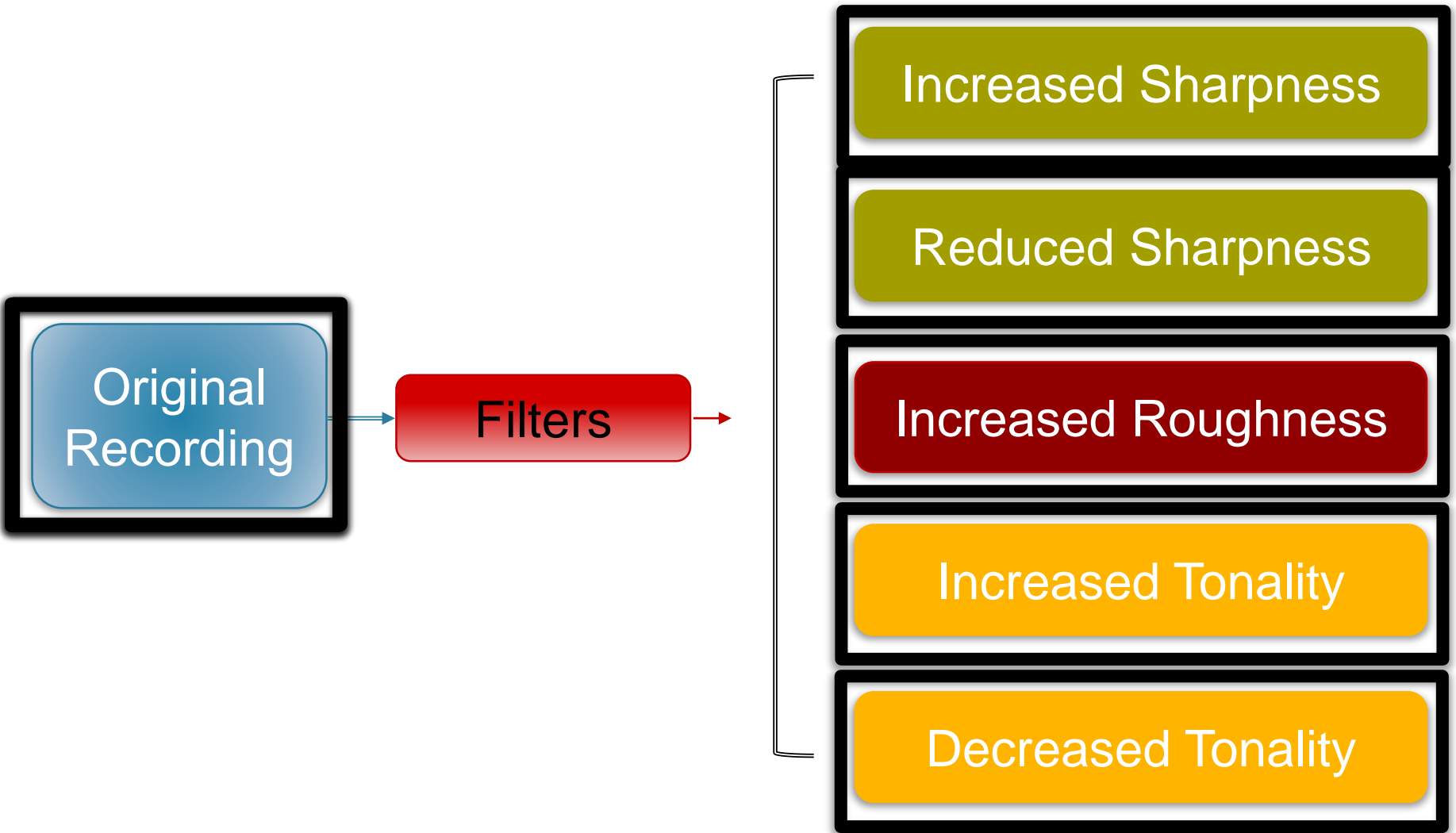
Test Sounds Selection

- Divide each correlation plot into 25 boxes
- Select sounds from loudness vs. roughness plot
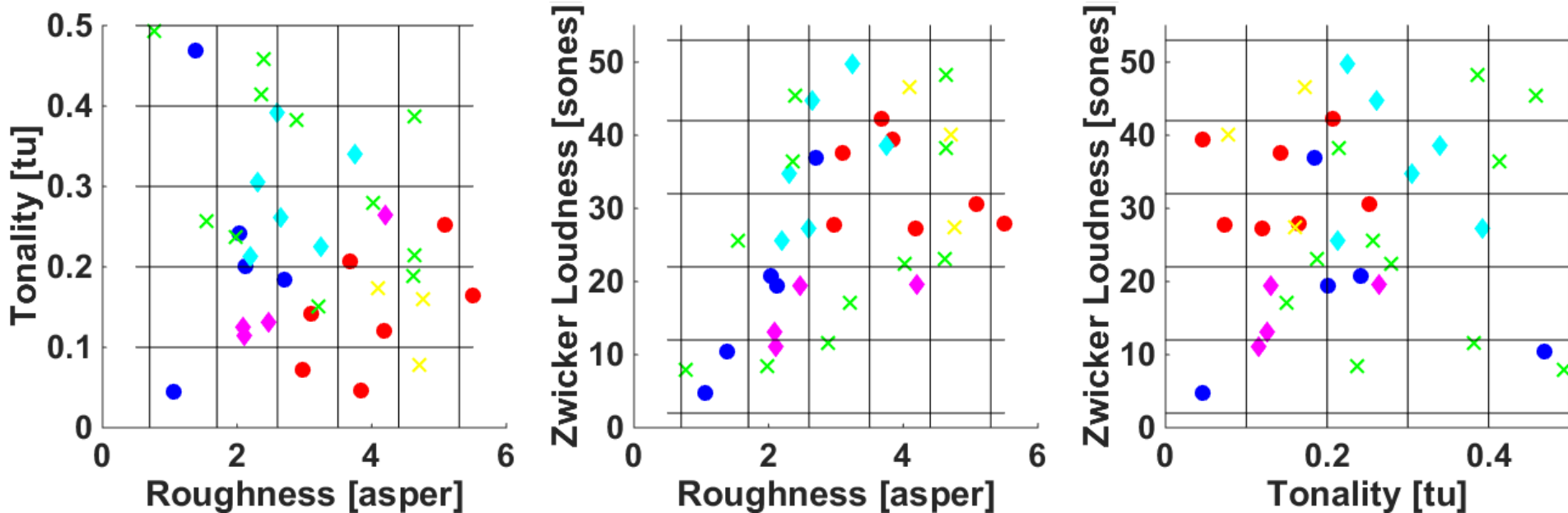
- Total 36 sounds
    - 14 mobile truck (7 original), 22 residential (5 original)

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

- Hearing Test

- Consent form & Questionnaire

- Listen to sounds for familiarization (5 sounds)

- Long list of sound descriptions (taken away)

- Practice describing

- **MAIN DESCRIPTION TEST**

- Test Scenario

- Practice rating

- **MAIN RATING TEST**

- Comments

- Repeat Hearing Test

- Payment

Approx. 1 hour

Test 1 MAIN PARTS

- Part A – Describe the Sounds

  - 24, 4 seconds HVAC&R sounds;

    played twice, 4 secs pause between each sound

  - Subjects describe each sound in their own words

- Part B – Rate the Sounds

  - 36, 4 seconds HVAC&R sounds

  - Test Scenario

  'While you are listening, it may be helpful to imagine yourself in your garden, at any time during the day or evening, hearing these sounds continuously'

  - Subjects rate the annoyance level of sounds

1	2		3.5		5		6.5		8	9
Not at all			Slightly		Moderately		Very		Extremely	
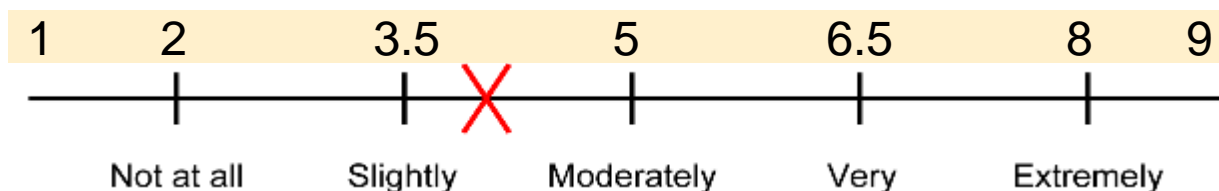
Subjects & Demographics

- Total Number of Subjects: 42
- Average Age: 27(18 – 57)
- Median Age: 25

Male	Female
23	19

Caucasian	Asian	South American
25 (4 mixed race: 2 White-Hispanic, 2 White-Black)	16 (2 grew up in U.S.)	1

Examples of Results – Description Test

Sound	Descriptor (Number of times used)	Average Annoyance Rating
151	high frequency(2), irritating(2), racing car, helicopter(3), disturbing(2), drilling(6), shaking, heavy, loud(6), unbearable, annoying(4), old, pulsing, cutting(2), old tractor, motorcycle(3), choppy(3), rattle, intense, whirring, weed wacker, summer(3), rotation, bumpy, rough(2), deep, abrupt, consistent, harsh(2), near, propeller(3), grinding(2), chisel, very fast(2), crackling, distorted(2), isolated, distinct, broken muffler, wood chipper, electrical saw, vibration, banging, grrr	5.96
76	processing, vacuum(3), light vehicle move, distant(3), white noise, bearable, light(4), familiar, safe, typical, low noise(2), blender, digital, bees, acceptable, fan(3), medium(3), muffled, dull, hum(3), buzz, quiet, calm(5), cool(2), relaxed(3), home, lightly rough, soft(9), air blowing(4), itchy, uneven, spinning(3), long, washing(2), sucking, factory(2), systematic, problematic, inefficient, hurrr, powerful, generator, grinding, pleasant, dryer, whirring, distorted, faint, even	3.92

Level related expression
Annoyance related expression
Sound quality metric related expression

14

Classification of Descriptors

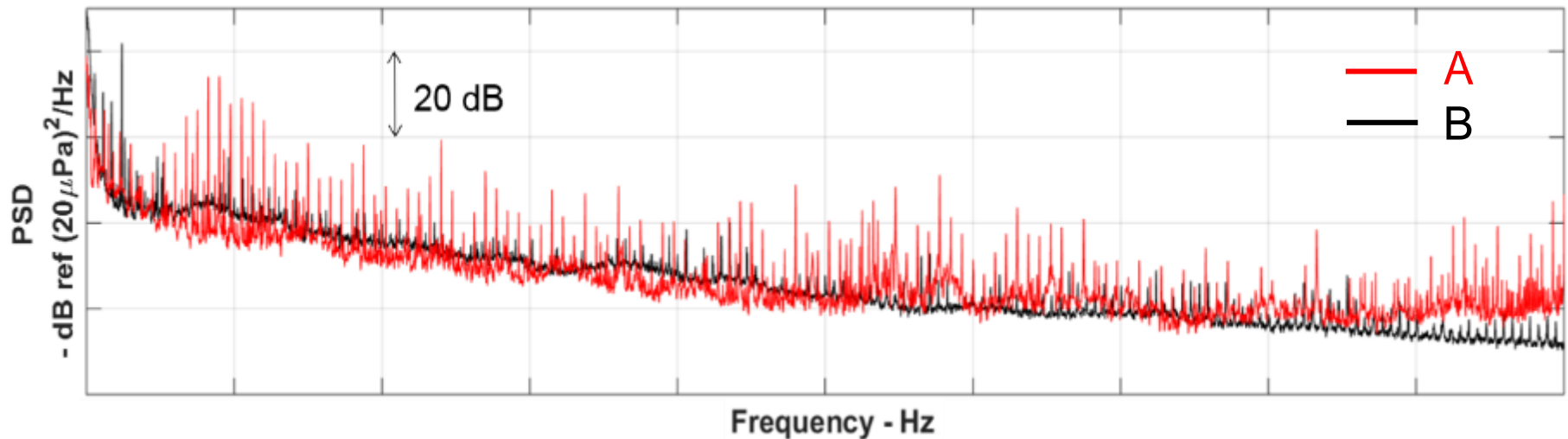| Classifications	Descriptor (number of times used)
Soft / Loud	Soft (56), Quiet (29), Muffled (16), Mild (10), Faint (7), Gentle (3) Medium (19), Moderate (17) Loud (210), Powerful (11), Intense (9), Strong (5), Vigorous (2), Not Soft (3)
Not Tonal / Tonal	Low (252), Low Frequency (12) Medium Frequency (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)
Smooth / Rough	Smooth (26), Even (5), Not Harsh (2) Whirling (25) Buzz (24), Harsh (23), Rough (15), Grinding (17), Rumble (16)
Fluctuating	Vibration (67), Pulsating (7), Uneven (6), Shaking (5), Beating (2), Oscillating (2) / Constant (7), Even (5)
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)

Word scores in Categories vs. Annoyance Rating

	++
	+
	NM or 0
	-
	--

NM - Not Mentioned

Signal	(+) Soft/ Loud (-)	(+) Not Tonal/ Tonal (-)	(+) Dull/ Sharp (-)	(+) Smooth/ Rough (-)	Fluctuat -ing (-)	Impulsive -ness (-)	(+) Pleasant/ Annoy -ing (-)	Average Annoyance Rating	(+) Emotional Response (-)	(+) Functional -ity (-)
13	++	NM	+	+	NM	NM	+	2.20	++	+
11	++	-	+	+	-	-	+	2.64	++	NM
35	++	--	+	-	--	-	+	3.48	+	+
10	++	-	-	-	-	-	+	3.52	+	+
31	+	-	NM	+	-	NM	+	3.84	+	-
30	++	-	+	-	0	NM	+	3.92	+	-
23	+	-	0	-	-	--	+	4.02	-	NM
26	+	-	NM	-	-	NM	-	5.06	0	+
4	-	-	-	-	-	--	-	5.29	NM	NM
20	+	-	-	+	-	+	-	5.50	-	NM
3	-	-	-	-	-	--	-	5.70	-	NM
2	-	-	NM	-	--	--	-	5.72	NM	NM
18	-	+	NM	-	-	--	-	5.84	-	NM
5	-	-	-	-	-	--	-	5.96	NM	NM
32	--	--	--	+	-	NM	-	5.99	-	-
33	--	--	NM	-	-	-	-	6.02	NM	NM
17	--	-	-	--	--	--	--	6.59	-	NM
7	-	--	-	--	-	-	-	6.65	NM	-
8	--	+	--	--	-	-	-	6.92	NM	-
9	--	-	-	--	-	-	--	7.19	-	-
28	--	-	-	-	-	NM	--	7.37	-	NM
22	--	--	-	-	-	-	--	7.44	-	NM
19	--	-	-	--	-	-	--	7.47	-	-
25	--	-	--	--	-	-	--	7.90	--	-

Metric Analysis and Outliers
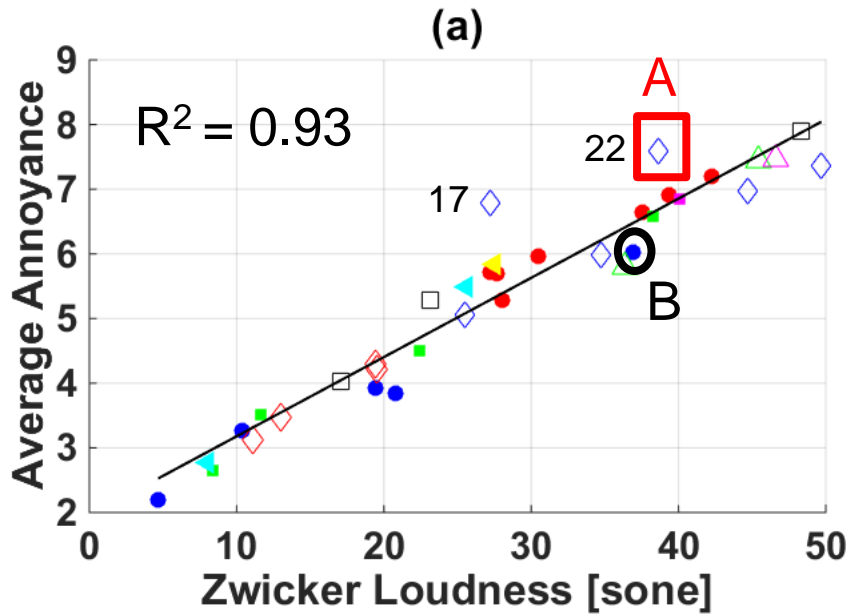
|	A	B	A	B
N_5	38.60	36.90	High pitch, loud, annoying, metallic, sharp, penetrate, cutting wood, sharp drill, whiny, painful, pounding	Loud, humming, vibration, white noise, low, low pitch, whirring, buzz, large fan, smooth, irritating
R_5	3.76	2.72		
F.S.	0.008	0.014		
S_{VBS}	1.48	1.08		
Tonality	0.34	0.18		
Aures Tonality	0.31	0.23		

Summary and Conclusions

- Descriptors from subjects were categorized into 9 groups

- Word scores were calculated by assigning numbers to descriptors

- Linear models of metrics to predict annoyance examined

- People noticed many different sound characteristics in addition to loudness

- Descriptions were consistent with annoyance ratings

- Zwicker loudness exceeded 5% of the time was the metric most highly correlated with annoyance

- Outliers in Test 1 (17 and 22) were described as:
  sharp, tonal, high pitched, loud, headache

- Categories were used to define end of scales in Test 2

Future Work

- ## Test 2
  - Semantic differential test was designed by using the descriptors from Test 1

- ## More signal modification techniques
  - Modify sharpness and tonality of the sound without changing loudness

- ## Test 3
  - Three sets of rating tests (organized by range of loudness)

T3 Part B (Loud)

Loudness [sone]

50
45
35
25
15
10

Common Region

T3 Part A (Quiet)

T3 Part C
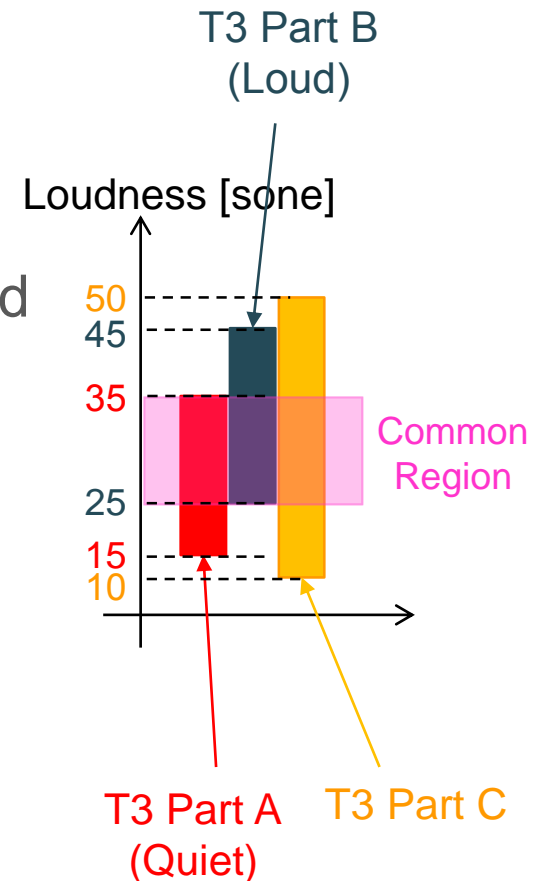
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Thank you!

Test 1 – List of Words

Afar, abrupt

bang, bark, bawl, bay, belling, bellow, blare, blatter, bleat, bong, boom, bowwow, brawl, bray, brushing, burning, buff, buzz, brief, burst, bouncing, beat

cackle, caterwaul, caw, chafing, chatter, cheep, cheer, chirp, chirrup, chuck, chuckle, clack, clang, clank, clap, clash, clatter, click, clink, cluck, clunk, coarse, coo, crack, crackle, creak, croak, crow, crunch, cry, cuckoo, can dropped, complicated, crinkle

drone, drumming, dropping, door opening (closing, shut), dull, distant, deep, dark

echo

fizz, fizzle, flutter, fritiniancy, falling object, flat, flexible, familiar, full

gaggle, giggle, gobble, grate, grating, grinding, groan, growl, gruff, grum, grumble, grunt, gruntle, guffaw, guggle, gurgle, glass, halloa, halloo, harsh, hiss, hoarse, hollow, hoop, hoot, horrisonous, horse, howl, howl, high-pitched, howl, low-pitched, hum, heavy object, hitting the floor, high frequency, hard, high

insect cry, itch

jangle, jar, jingle

knock

latration, laugh, low, loud, long, light, low pitch, low frequency

meow, mew, mewl, moan, moo, metallic, musical, medium pitched, muffled

neigh, noisy, near

oil canning, ooh-tone

patter, peep, ping, pipe, pop, pounding, pule, purr, plastic container, paper on table, paper in it

quack, quick

rap, ratting, rattle, rebellow, reboation, ring, roar, rough, rumble, rustle, rapid, repetitive, resounding, rigid, rolling off, reverb, resonant

screak, scream, screech, screech owl, scrub, sepulchral, shout, shriek, shrill, sizzle, slap, snap, snarl, sneeze, snigger, snore, snort, snuffle, squall, squash, squawk, squeak, squeal, stridulous, swish, swoosh, slow, short, slam, smooth, soft, simple, strange, sustained, sharp, stompting, scratched

tapping, thrumming, thud, thump, tick, ting, tinkle, tittler, troat, twang, twirling, twitter, thunder

ululation, unintelligible

vibratory

wheeze, whine, whirl, whirring, whistle, whiz, whoop, woodnote, whip, wiggle

yap, yarr, yaup, yawl, yell, yelp