Comparison between perceptual responses to traffic noise and wind farm noise in a non-focused listening test

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ABSTRACT

Despite the clear benefits of renewable energy, the rapid expansion of wind energy has resulted in widespread community complaints regarding wind farm noise (WFN). As the impact of WFN on sleep and health is not well established, road traffic noise (RTN), with well-known sleep disturbance effects, is likely to be a useful environmental noise comparator. This study investigated the self-reported annoyance to short- and long-range WFN and RTN via a non-focused listening test. Twenty-five participants from a WFN-naïve sample population took part in the listening test. A total of six stimuli were presented in random order for 10-min each, while participants were engaged in a reading task. Five WFN and RTN stimuli were presented at a sound pressure level (SPL) of 33 dB(A) for comparison with the sixth 'no noise' background control stimulus, which had an SPL of 23 dB(A). After each stimulus, participants responded to questions regarding annoyance, awareness, acceptability for sleep and loudness. Participants were also instructed to order the samples from the least to the most annoying. Short- and long-range WFN and short-range RTN were consistently rated as the most annoying according to sample ordering. There were significant differences between subjective responses to noise samples versus the 'no noise' control , however, no significant differences in subjective reports toward specific noise samples.

1 INTRODUCTION

Several important characteristics of wind farm noise (WFN) have the potential to disturb humans. These include the dominance of low-frequency components, which have the potential to disturb rest and sleep at relatively low noise levels (Berglund, Lindvall, and Schwela 1999). Also, the time-varying nature of the noise results in potentially annoying characteristics such as 'swish', 'thumping' and/or 'rumbling' (Stigwood, Large, and Stigwood 2013, Renewable UK 2013, SA Environmental Protection Authority 2013). Moreover, disturbance could arise due to the large contrast between operational and ambient conditions, particularly at night-time, in the normally quiet rural environments where wind farms are usually located in Australia (Hansen, Zajamšek, and Hansen 2014).

Previous listening tests have investigated the effect of various WFN components on annoyance (see Alamir, Hansen, and Zajamsek (2018) for review). The main focus of these studies has been on signals measured less than 1 km from a wind farm (Lee et al. 2011, Ioannidou, Santurette, and Jeong 2016, Schaffer et al. 2016, Yokoyama, Sakamoto, and Tachibana 2014), where the noise is dominated by mid-frequency energy. These studies have shown that annoyance ratings increase in response to an increase in sound pressure level (SPL) (Renewable UK 2013), AM depth (Lee et al. 2011, Ioannidou, Santurette, and Jeong 2016, Yokoyama, Sakamoto, and Tachibana 2014, Schaffer et al. 2016) and tonal audibility (Yokoyama and Tachibana 2016). Listening tests using synthesised WFN based on measurements taken between 100 m and 1 km from a wind farm showed that low-frequency components less than 63 Hz have minimal effect on perceived loudness (Yokoyama, Sakamoto, and Tachibana 2014). However, these results may not extrapolate to all WFN measured at distances greater than 1 km, where the spectrum is dominated by low-frequency energy. One key reason may be that for a specific change in low-frequency content to have an equivalent effect on subjective annoyance as the same change in mid- and high-frequency content, a difference of at least 30 dB between the low-frequency and the mid/high-frequency content is necessary (Torija and Flindell 2015). Another reason may be that the results obtained by Yokoyama *et. al*. (2014) are only applicable to steady signals and are not representative of WFN containing low-frequency tones and AM.

Results of listening tests investigating other sources of low-frequency noise are also relevant to WFN research, particularly where special audible components such as tonality and AM are present. Persson-Waye *et al*. (2001) found that low-frequency amplitude modulated tonal noise can adversely affect performance of tasks involving sustained attention and awareness over 30 min. However, the noise samples were based on low-frequency ventilation noise containing a tone in the 31.5 Hz 1/3-octave band, which is at least 20 dB higher than tones at the same frequency measured outdoors near a wind farm (Cooper 2014). Also, the modulation frequency was 2 Hz, which is higher than typical values associated with large modern wind turbines with capacities greater than 2 MW (< 1 Hz). In another study, Persson-Waye *et. al.* (2003) observed that compared to a reference night with no exposure to noise, participants took nearly twice as long to fall asleep when exposed to low-frequency ventilation noise. The low-frequency ventilation noise investigated included a 50 Hz tone, which was amplitude modulated at 2 Hz. Similarly to the study by Persson-Waye *et. al.* (2001), the amplitude of the tone was at least 10 dB higher than tonal WFN measured outdoors in this 1/3-octave band and the modulation frequency was higher than that associated with WFN (Hansen, Zajamšek, and Hansen 2014). According to listening tests carried out by Oliva *et. al.* (2017), penalties for tonality are not required for low-frequency tones at 50 Hz and 110 Hz with tonal audibilities ranging from 5 to 25 dB(A). However, these results may have been influenced by the short sample time of 15 s, which may not have been long enough to capture the extent of annoyance. Also, while noise sensitivity was measured by Oliva *et. al.* (2017), it was not reported, and thus it is unclear if their sample included a balance of sensitive and non-sensitive individuals. Moreover, results may differ through use of a representative WFN background spectrum rather than a spectrum based on the inverse A-weighting curve.

The majority of WFN annoyance studies to date have investigated relatively short-range noise types dominated by ‘swish’. However, in an Australian context, low-frequency ‘thumping’ or ‘rumbling’ noise appears to be a more common complaint (Hansen, Nguyen, Zajamšek, et al. 2019). This study investigates the human response to this ‘thumping’ or ‘rumbling’ noise that has been mentioned in complaints from residents. The noise consists of a 50 Hz tone that is amplitude modulated at the blade-pass frequency, hereafter referred to as WFN AM. The response to WFN AM is compared to other noise types including, short- and long-range road traffic noise (RTN), ‘swish’, WFN without AM and ambient noise. The aim of the study was to investigate the human perception of the various noise stimuli during a relatively long exposure time of 10 minutes, whilst participants were engaged with reading. Following noise exposure, participants rated their response to each noise type in terms of annoyance, awareness and perceived loudness. A further aim was to examine participants’ anticipated level of difficulty in falling asleep in the presence of different noise types.

2 METHODOLOGY

2.1 Participants

Twenty-five participants (56% females) aged between 18 and 75 years old (mean (M) ± standard deviation (SD): 25.1 ± 12.5) took part in this listening test. All participants had hearing within the normal range according to clinical audiology exams conducted by a qualified audiologist. Self-reported noise sensitivity was obtained for each participant via the 21-question Weinstein noise-sensitivity scale (WNSS) test (Weinstein 1978). The WNSS focuses on general environmental noise rather than WFN specifically. Responses to each of the 21 items are scaled along 6 points with 0 indicating *strong disagreement* and 5 indicating *strong agreement*. After reverse coding relevant items, the unweighted sum of scores from each of the items is tallied. Stronger agreement with the items results in a higher score (ranging from 0 to 105), indicating greater individual noise sensitivity. For the listening test, participants were given general instructions regarding study procedures but remained unaware of the specific nature of different noise types. None of the participants lived near a wind farm or reported prior exposure to wind farm noise in their home setting. Noise samples were presented in random order and participants remained blinded to specific noise types. This study was approved by the Flinders University Social and Behavioural Research Ethics Committee (SBREC project 7536). All participants provided voluntary informed written consent and were financially reimbursed for the time and involvement in the project.

2.2 Testing room and instrumentation

Listening tests were undertaken at the Flinders University Sleep Laboratory, Bedford Park. This laboratory has been acoustically treated to minimise ventilation noise and transmission noise from adjacent spaces and the background noise level was measured to be 23 dB(A).

The noise samples were reproduced using an RME babyface Pro sound card, a Lab Gruppen amplifier and Krix loudspeakers. Sound calibration of the overall SPL was carried out at the participant's head to ensure faithful reproduction of the SPL of each sample.

2.3 Stimuli

The stimuli were selected from field data that were measured using specialised low-frequency microphones. Six stimuli were used, including:

Long-range:
1. 'Rumbling' - WFN with amplitude modulation (AM) (3.3 km from nearest wind turbine)
2. WFN without AM (3.3 km from nearest wind turbine)
3. RTN (700 m from the nearest main road)

Short range:
4. 'Swish' - WFN with AM (500 m from nearest wind turbine)
5. RTN (20 m from the nearest main road)

Control:
6. Ambient noise

The stimuli were presented at an SPL of 33 dB(A), the control ambient noise SPL was 23 dB(A) and the duration of each sample was 10 minutes. The spectra of the test stimuli are shown in Fig. 1.

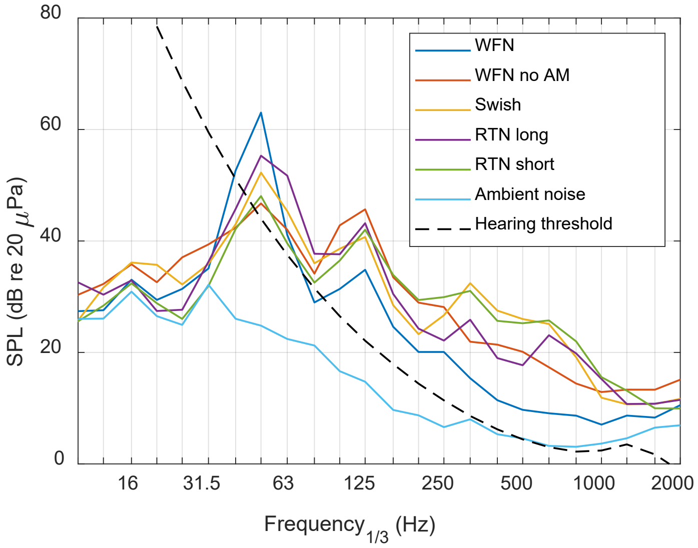

Figure 1: Stimuli used in the listening test.

2.4 Experimental procedure

The stimuli were reproduced through a MATLAB graphical user interface (GUI) that was developed to guide the participants through the 1-hour listening test (see appendix for questions and associated rating scales) and to record their response to each question. Participants were instructed to sit quietly and relax, while reading any material of their choice. After each 10-min noise presentation, participants were given as long as was necessary to respond to a range of questions about the preceding noise sample. The questions targeted the participants' feelings toward the noise in terms of:

1. General annoyance
2. Annoyance for reading
3. Awareness
4. Anxiety/distress associated with falling asleep in its presence
5. Anticipated difficulty in falling asleep in its presence
6. Loudness

The participants were also asked to rank the noise stimuli from the least to the most annoying both at the end of each noise presentation and after listening to all 6 noise presentations. At the latter stage of the test, participants were given the opportunity to replay the noise samples for as long as they necessary, up to a maximum of 10 min to assist them with their final ranking from (1) least annoying to (6) most annoying.

3 RESULTS

According to the WNSS, the participant noise sensitivity score ranged between 32 and 70 (M ± SD: 47.8 ± 10.2). To classify participants as noise sensitive/non-sensitive in this study, it was not possible to use the same methodology as employed by Weinstein (1978). Weinstein (1978) classified participants with noise sensitivity scores in the lowest and highest thirds as least and most sensitive, respectively. In this study, Weinstein's approach may have yielded a misleading result due to the small sample size. Therefore, the mean value of sensitivity determined by Weinstein (1978) (n = 155) was used to divide the participants into noise sensitive/non-sensitive groups, such that those who scored below the mean were less sensitive to noise and those scoring above the mean were more noise sensitive. According to this definition, only 3 participants were classified as noise sensitive.

A one-way ANOVA analysis was carried out to compare the subjective ratings given in response to the 6 questions outlined in Section 2.4 for the six noise stimuli. Results from the one-way ANOVA analysis indicated that there was a significant difference between noise types ($p < 0.05$). Pairwise comparisons between noise samples using the Tukey Honest Significant Differences and Bonferroni tests showed significant differences in subjective responses to all 6 questions between ambient noise compared to all other noise stimuli ($p < 0.05$), and no statistically significant differences between any of the noise stimuli. The mean ratings for the different noise stimuli shown in Figure 2 varied by 0.5 points at most, indicating a small effect size. While the mean rating differences between noise stimuli were relatively small, the standard deviation was large, indicating considerable inter-individual variability.

Mean ± Standard deviation values shown in Figures 2 (a), (b), (d) and (e) indicate that compared to traffic and 'swish' noise, participants consistently rated wind farm noise containing AM as the most annoying and potentially disturbing for sleep. Responses to the other noise types were less consistent, although long-range RTN typical of suburbia, was generally considered to be the least annoying and disturbing for sleep. In the absence of AM, WFN was generally rated lower for annoyance and sleep disturbance compared to other noise types. This suggests that the AM component of the WFN could be linked with increased annoyance and sleep disturbance of WFN AM compared to other noise types.

Despite the fact that WFN AM was considered more annoying and disturbing for sleep, Figures 2 (a) and (f) show that participants gave it a relatively lower rating when assessing their awareness of the noise and perceived loudness. This suggests that perceived loudness and awareness are not necessarily strong predictors of annoyance and sleep disturbance.

Visual inspection of Figures 2 (b), (d) and (e), which use the same rating scale, shows that ratings associated with sleep disturbance were higher than those associated with annoyance. This may indicate that the absence of noise is valued more highly during attempts to sleep compared to undertaking a quiet leisure activity such as reading.

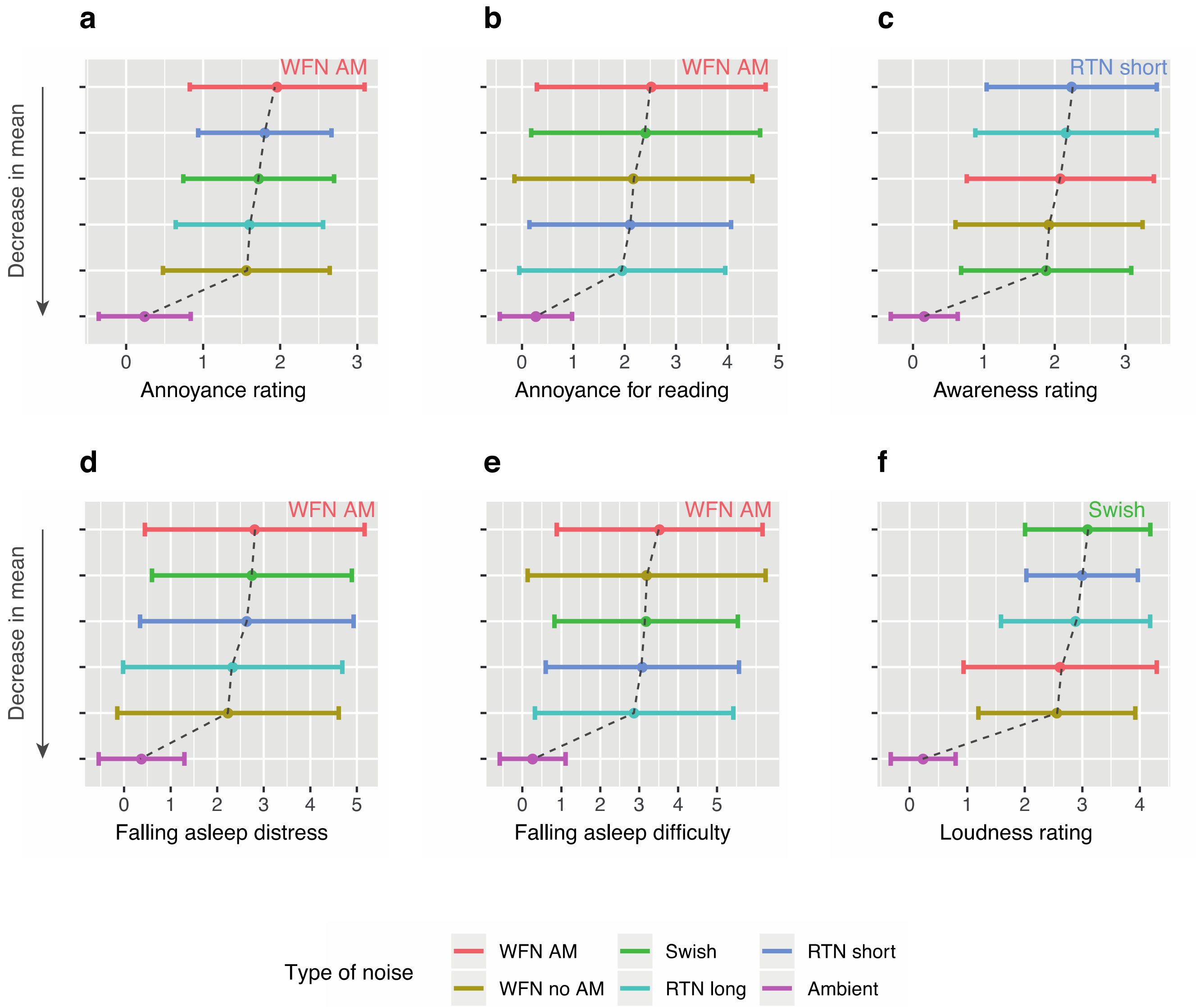

Figure 2: Comparison between the human perception of different noise stimuli, showing the mean and standard deviation. The Likert-type rating scales were as follows: (a) 0-5, where 0 = did not notice and 5 = very annoying, (b,d,e) 0-10, where 0 = not at all and 10 = extremely, (c) 0-4, where 0 = hardly or not aware of it at all and 4 = the whole time and (f) 0-10, where 0 = no sound and 10 = uncomfortably loud.

As participant responses were not always normally distributed, the median ratings of annoyance for reading and difficulty in falling asleep are shown in Figures 3 (a) and (b). Visual inspection of the median response indicates that WFN AM was considered the most annoying and disturbing for sleep. Without AM, WFN was considered as the least annoying noise stimulus for reading. Long-range RTN was rated as the noise stimuli with the least potential to cause difficulty for falling asleep. In general, the median provides similar information to the mean.

The inter-individual variability of subjective ratings is particularly evident in Figures 3 (a) and (b) which show that for the same noise type, the ratings ranged from 1 to 9 for annoyance and 1 to 10 for difficulty in falling asleep. This indicates that for the same noise type, one individual found that the noise would be not at all disturbing for falling asleep whereas another individual found that it would be extremely disturbing. This is in contrast to the response to control ambient noise, where the ratings varied between 1 and 3, showing that all individuals judged the ambient noise to be not more than slightly disturbing for falling asleep. The 95% confidence intervals are larger in Figure 3 (b) compared to Figure 3 (a), which suggests that perceived difficulty in falling asleep in the presence of noise varies widely between individuals.

To further explore the inter-individual differences in response to noise, cumulative distribution function (CDF) plots were constructed as shown in Figures 3 (c) and (d). These plots indicate the percentage of individuals reporting various ratings in response to the different noise stimuli, where values of 0 and 1 correspond to 0% and 100% of participants, respectively. Visual inspection of Figures 3 (c) and (d) indicates clear differences between ambient noise and the noise stimuli, however, differences between the various noise types appear to be relatively small. Nevertheless, Figure 3 (c) shows that a larger percentage of people gave higher annoyance for reading ratings to WFN AM compared to other noise stimuli. For instance, 20% of participants rated WFN AM between moderately and extremely annoying, whereas the equivalent annoyance was only expressed by 5 and 8% of participants in response to short- and long-range RTN, respectively. Also, 30% of participants rated WFN AM as having the potential to make falling asleep moderately to extremely difficult, compared to 25 and 12% of participants for short- and long-range RTN. Although more participants gave WFN without AM a rating close to 'extremely' for 'difficulty for falling asleep' compared to WFN without AM, the ratings on the right-hand side of the CDF plots are less reliable as they pertain to only one or two participants and therefore they should be interpreted with caution. Thus, although substantial differences between noise types were not observed, the overall trends indicate that a larger percentage of participants found WFN AM the most annoying with the greatest potential to cause difficulties for falling asleep.

The initial rank order of the least to the most annoying that was chosen by the participants and shown in Figure 4 (a), indicates that the highest percentage (32%) of participants considered WFN AM to be the most annoying stimulus. This was closely followed by short-range RTN and swish, which were rated as the most annoying by 28 and 24% of participants, respectively. Ambient noise was rated as the least annoying stimulus by 92% of participants, whereas 8% of participants rated short- and long-range RTN as the least annoying, possibly due to their greater familiarity with this noise type. When given the opportunity to replay the noise stimuli and adjust their rank order, 44% of participants changed the order and the corresponding results shown in Figure 4 (b) indicate that the overall group response changed noticeably. In this case, short-range RTN and WFN AM switched positions as the most and the second-most annoying stimulus according to 32 and 28% of participants, respectively. Although ambient noise maintained its position as the least annoying stimulus according to the majority of participants, it was rated less favourably than in the initial ranking. Despite the noise ranking adjustments made by participants, the overall trends remained similar and WFN AM was still ranked as the most or the second-most annoying stimulus.

A possible reason for the differences between Figures 4 (a) and (b) is that the length of replayed stimuli may have affected participant responses as annoyance to noise can be time-dependent (Hansen, Nguyen, Zajamsek, et al. 2019). Also, participants were fully focused on the noise instead of engaging in reading and therefore their response may have been influenced by their awareness of the noise and its perceived loudness. As shown in Figures 2 (c) and (f), noise stimuli giving rise to greater awareness and perceived loudness were not the most annoying in the case of a 10-min exposure. Therefore, the rank order recorded after the last noise stimulus is considered to be more representative for relatively long exposures during reading. The unexpected response to the baseline stimulus shown in Figure 4 (b) gives further evidence that the results shown in Figure 4 (a) provide a more accurate representation of the rank order.

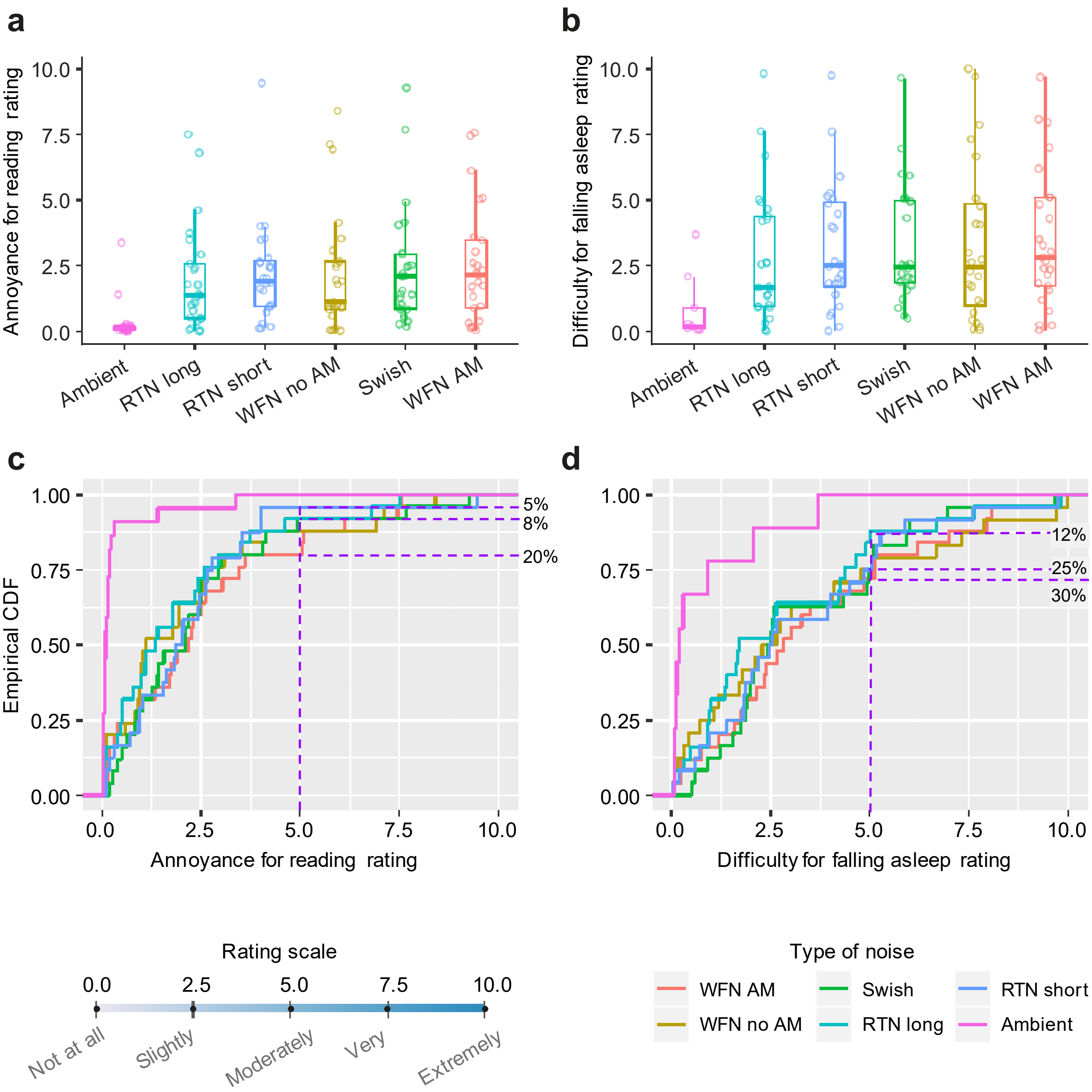

Figure 3: (a,b) Boxplot showing median and interquartile ranges indicating human response to the noise stimuli in terms of annoyance for reading and difficulty for falling asleep. (c,d) Cumulative distribution function showing variability between participants. Dashed purple lines indicate percentage of participants moderately/extremely annoyed/disturbed by WFN compared to RTN.

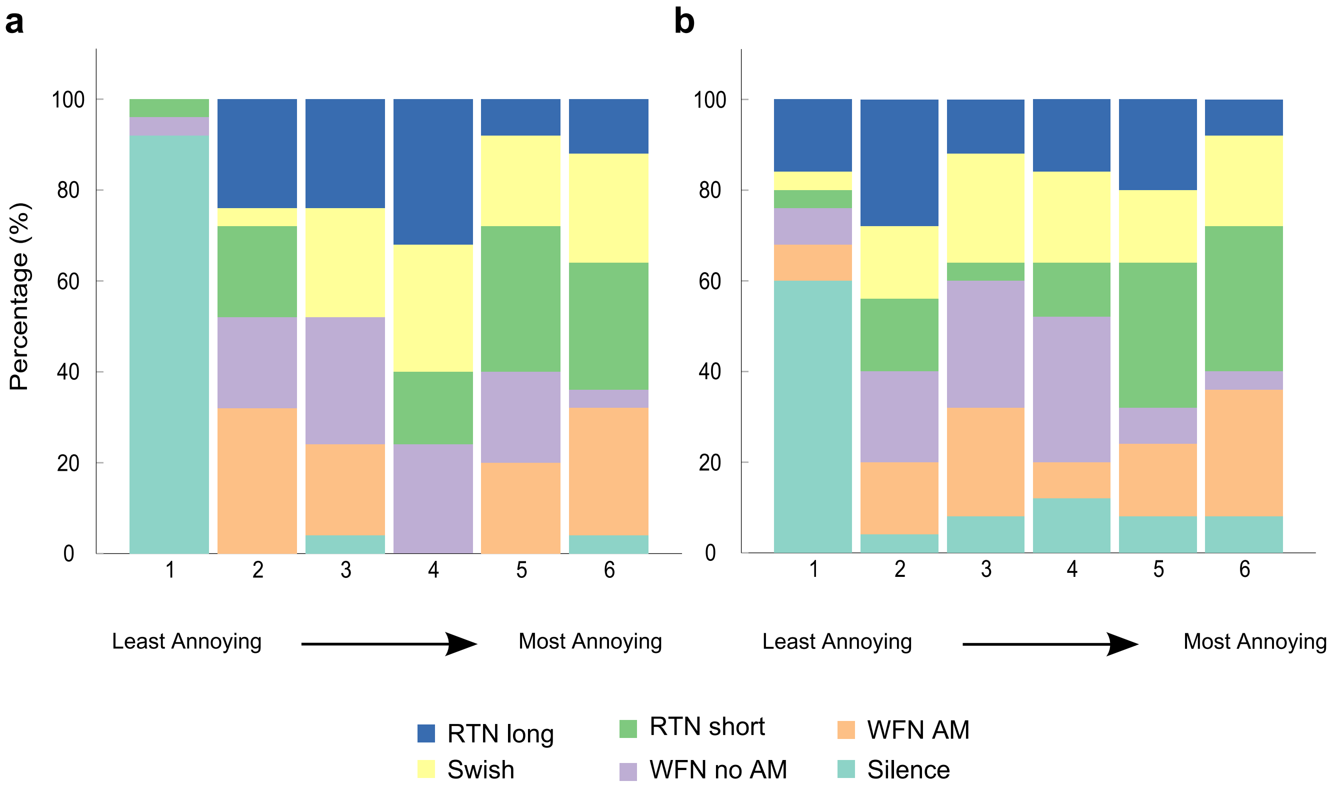

Figure 4: Stacked bar chart showing annoyance ranking of the various noise stimuli, where 1 = least annoying and 6 = most annoying. (a) After final stimulus and (b) After given the opportunity to play short segments of each noise stimulus again.

4 DISCUSSION AND CONCLUSIONS

According to participant responses during a non-focused listening test, low-frequency WFN measured at 3.3 km and containing AM was rated as the most annoying noise stimulus with the greatest potential to cause sleep disturbance. Long-range RTN measured 700 m from the nearest main road, was often rated as the least annoying noise stimulus with a relatively low potential to cause sleep disturbance. Hence, at the same sound pressure level of 33 dB(A), there was some evidence to support that WFN containing AM may be more annoying and disturbing for sleep than suburban traffic noise to which a large percentage of the urban population may be more accustomed. However, there were no systematic differences between noise types, which could indicate that different noise types are perceived as quite similar in terms of their potential to annoy and/or disturb sleep. On the other hand, the sample population, which consisted mainly of urban-dwelling students may not be representative of a rural-dwelling population of greater relevance to WFN exposure. Furthermore, given very few self-reported noise-sensitive individuals, further work to compare responses in larger groups of WFN exposed versus non-exposed and self-reported noise sensitive and insensitive groups remains warranted. Self-reported potential difficulty in falling asleep is particularly useful for comparisons between noise types, but further work remains needed to more specifically and objectively examine WFN versus RTN effects on sleep itself.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support from the Australian Research Council, Projects DP120102185 and DE180100022 and fellowship FT120100510 and the National Health and Medical Research Council, Project 1113571. We would also like to give a special thanks to the participants who took part in this Pilot test.

APPENDIX - LISTENING TEST QUESTIONS

1. Please rate your **annoyance** to the sound you just heard:
   - **0.** Did not notice
   - **1.** Noticed but not at all annoying
   - **2.** Barely annoying
   - **3.** Somewhat annoying
   - **4.** Rather annoying
   - **5.** Very annoying

2. How much were you **bothered, disturbed** or **annoyed** by the sound while trying to read?

0 1 2 3 4 5 6 7 8 9 10

Not at all (0) · Slightly (2.5) · Moderately (5) · Very (7.5) · Extremely (10)

3. How much of the time were you **aware** of the sound?
   - 0. Hardly or not aware of it at all
   - 1. Only for a short time
   - 2. Often
   - 3. Nearly the whole time
   - 4. The whole time

4. If you were trying to **fall asleep** in the presence of this sound how **distressed/anxious** would you feel?

0 1 2 3 4 5 6 7 8 9 10

Not at all (0) · Slightly (2.5) · Moderately (5) · Very (7.5) · Extremely (10)

5. If you were trying to **fall asleep** in the presence of this sound how **difficult** would it be?

0 1 2 3 4 5 6 7 8 9 10

Not at all (0) · Slightly (2.5) · Moderately (5) · Very (7.5) · Extremely (10)

6. How **loud** was the sound?

0 1 2 3 4 5 6 7 8 9 10

No sound · Soft · Medium · Loud · Very loud but comfortable · Uncomfortably loud

7. Please think back and rank order the sounds from 1 – **Least annoying** to 6 – **Most annoying**:

After sound 1	After sound 2	After sound 3	After sound 4	After sound 5	After sound 6
Think about how annoying you found the sound you just heard. After the next sound we will ask you to start ranking them relative to each other.	Sound 1 ___ Sound 2 ___	Sound 1 ___ Sound 2 ___ Sound 3 ___	Sound 1 ___ Sound 2 ___ Sound 3 ___ Sound 4 ___	Sound 1 ___ Sound 2 ___ Sound 3 ___ Sound 4 ___ Sound 5 ___	Sound 1 ___ Sound 2 ___ Sound 3 ___ Sound 4 ___ Sound 5 ___ Sound 6 ___

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