DOI: 10.61782/fa.2023.0374

INVESTIGATION OF HELICOPTER NOISE ANNOYANCE AND NOTICEABILITY IN URBAN ENVIRONMENT

Elise Ruaud[*1] **Ingrid LeGriffon**[1] **Julien Caillet**[2]
[1] DAAA, ONERA, Chatillon, France
[2] Airbus Helicopters, Aéroport International Marseille-Provence, France

ABSTRACT

Helicopters are often operated in urban areas, potentially leading to an additional source of annoyance for the inhabitants. In an already complex urban noise environment, masking effects can influence this negative perception. To deepen the understanding of helicopter noise annoyance, it is interesting to include background noise and the concept of noticeability when evaluating the impact of helicopter noise.

Two listening tests have been carried out to study the annoyance caused by helicopter noise, the noticeability of these sounds in certain noise environments and the link between these two phenomena. Auralized helicopter sounds were played over a background noise while participants were reading novels. For each stimulus, participants graded on a numerical scale the annoyance and/or the interference on their reading activity caused by the flyover. The statistical analysis enables to 1) examine the link between flyover characteristics and annoyance as well as the link between flyover characteristics and noticeability, 2) establish a correlation with acoustic and psychoacoustic parameters such as A-weighted sound pressure level, loudness, sharpness, detectability level and roughness, 3) study the correlation between the noticeability of helicopter noise and annoyance.

Keywords: *Helicopter noise, annoyance, noticeability, listening test*

[*] ***Corresponding author***: elise.ruaud@onera.fr.

1. INTRODUCTION

Although there have been a lot of advances on the understanding of transportation noise influence on human annoyance, there are still a lot of unknowns regarding the impact of helicopters' noise on inhabitants. As the ARCP report [1] summarizes in its literature review, "The findings of individual studies on the annoyance of helicopter noise disagree about as often as they agree.". The wide variety of helicopter noise is pointed out as one of the main difficulties in the psycho-acoustics studies.

Nevertheless, recently several studies improved the understanding of the perception of helicopter noise [2-6]. Thanks to the analysis of listening tests' results, they investigated the source of annoyance and linked it to the sound characteristics. In particular, some sound quality metrics (SQM) seem to be interesting indicators of the potential impact of the helicopter noise: sharpness, loudness, impulsiveness, roughness, tonality and fluctuation strength.

In addition to annoyance, the question of the noticeability of the helicopter is a complementary way to apprehend the impact of its noise on the community. Defined by Sneddon [7] as 'the ability of an audible signal to attract the attention of an individual engaged in an activity other than listening for such a sound', the noticeability evaluates the conscious detection of the helicopter while the individual is not actively listening. From the authors' knowledge, there are currently only few studies regarding the noticeability or the audibility of helicopter noise [7-8].

This study aims at deepening the understanding of the perception of helicopter noise, in particular in the context of an urban environment. The ambition of this work is to link the characteristics of the flyover sound both to annoyance and noticeability.

Ideally, this link should be assessed in one listening test, in order to enable an easy comparison between different variables. However, while the annoyance has to be studied with stimuli clearly audible above the background noise, so that annoyance ratings are not entirely based on background noise levels; the study of the noticeability must be done with low signal-to-noise ratios. That is why this experiment is divided into two distinct listening tests. The first one, *T1*, focuses on the annoyance aspect with the two questions of the interference caused by the helicopter flyover on a reading activity and the comfort felt by the subject in a specific sound context. On the other hand, the second test, *T2*, aims primarily at studying the noticeability of the sounds. In order to be able to look for links or draw common conclusions, the two tests have however very similar protocols. Both tests include a reading activity and the presence of background noise. Two different background noises are used in each test: one with kids playing on a playground and one with a road with cars regularly passing by at mid-distance.

This paper will present the two listening tests from the conception of the synthetized stimuli to the instructions given to the participants and a selection of the results of the statistical analysis. However, since we choose to detail the listening test set up in this paper, the presentation of the statistical analysis will be limited to the study of the interference across the two tests.

2. STIMULI AND BACKGROUND NOISE

2.1 Synthesis of the stimuli

The Airbus Helicopters computational chain used to produce the helicopter stimuli relies on three different tools, CAROT (Compute Acoustics of a Rotorcraft Over Terrain) [9], ROSI (Rotor nOise Source Identification) and GenePASS (ANSYS) [10].

CAROT is an Airbus Helicopters in-house tool able to evaluate the noise footprint of a rotorcraft flying a given trajectory in a local coordinate system, from experimentally acquired helicopter noise sources. An aeroacoustic database has been built from dedicated flight tests measurements of rotorcraft noise in multiple steady-state flight conditions. The noise source is modelled as a hemisphere aiming at well capturing the directivity of main and tail rotor noise. The trajectory is then sampled in equally time-spaced emission instants. Every considered emission instant is linked to a steady-state flight condition. True Air Speed (TAS) and aerodynamic slope are used as noise governing parameters to retrieve the emitted noise data from the aeroacoustic database. Additional effects of acceleration/deceleration as well as wind effect on noise emission are taken into account through a quasi-static approach. The emitted noise data are then propagated to a set of user-fixed positions on the ground. Recent developments of the tools aiming at improving computational efficiency and prediction capability have been presented [9].

In this study, a H130 light-single helicopter of Maximum Take-Off Weight around 2.5 tons has been chosen as reference noise configuration. Its available noise source database has been decomposed into three components for each flight condition: a main rotor tonal hemisphere, a tail rotor tonal hemisphere, and a residual noise broadband hemisphere, through application of the Airbus helicopters in-house tool ROSI which identifies and extracts from an acoustic input signal the particular noise signals caused by specified rotational sources (the rotors here).

The helicopter pass-by is then auralized at a given listener position on ground thanks to the commercial software GenePASS that synthesizes a time history signal from the individual contributions of the three component noise signals obtained with CAROT free field propagation. The three hemispheres are combined to create three different 'signatures' for the stimuli: the total flyover of the helicopter *tot*, the sound emitted by the flyover without the main rotor's contribution *woMR* and the noise without the contribution of the tail rotor *woTR* – the signatures *woMR* and *woTR* do not correspond to any real flyover but enables to distinguish the impact of the different rotors on the helicopter's perception. The summation is obtained from interpolations of the three components' source power spectral density synthesized as 20 ms resolution stationary signals. Ground effects (plane wave specular reflection model based on Delany-Bazley absorption) are added directly in GenePASS, as well as atmospheric turbulence effects. The listener position was chosen 100 m to the right of the helicopter trajectory; the participants therefore heard the sound moving from the left to the right in front of them. The spatialization of the sounds were performed with REAPER, taking into account the height and the speed of the helicopter.

For the two listening tests, several level-flight conditions have been auralized, the parameters (speed, height and signature) of the flyovers are summarized in Table 1.

A set of 12 stimuli was created for *T1*, with two flight speeds {95 kts; 126 kts}, two ground heights {500 ft; 1000 ft} and three different signatures {*tot; woMR; woTR*}. These parameters have been chosen so as to allow a wide distribution of maximum A-weighted noise level (L_{Amax}), Sound Exposure Level (SEL), and noise exposure duration. The values of these metrics for the auralized signals have been compared with available ground microphone measurements for the available test conditions, confirming an appropriate estimation of acoustic parameters with the simulation tool chain.

With the same reasoning, 15 stimuli have been synthetized for *T2* with few adjustments from *T1*'s stimuli set. After the analysis of *T1*'s results, some changes were made to the height, signature and sound level to adapt the stimuli to the study of the noticeability.

As expected, all the participants did notice the helicopter noises during *T1*. To study the noticeability in *T2*, it was then necessary to lower the signal-to-noise ratio. A relative negative gain of about 8 dB was applied to all the sounds so that approximately one third of the stimuli was not detected over the background noise when the participant was reading. Three additional 'control' stimuli were added with the same gain used in *T1* to allow a comparison between *T1* and *T2*.

Moreover, the roughness appeared to be slightly correlated to the loudness in the set of stimuli used in *T1*. To simplify the *T2's* statistical analysis and avoid any correlation between these metrics, it was decided to introduce new sounds at 1200 ft. With high roughness values for low loudness values, these stimuli decorrelated the evolution of the roughness from the sound level.

To keep the test duration below a reasonable time, the stimuli with a signature without main rotor *woMR* were removed from *T2* set of stimuli.

Table 1: Stimuli used in *T1* and *T2*. In *T2* the stimuli are played with a lower gain except the three control ones, marked with an asterisk.

T1	Speed [kt], Height [ft], Signature	*T2*	Speed [kt], Height [ft], Signature
0	95_500_tot	0	95_500_tot
1	95_500_woMR	1	95_500_woTR
2	95_500_woTR	2	95_1000_tot
3	95_1000_tot	3	95_1000_woTR
4	95_1000_woMR	4	95_1200_tot
5	95_1000_woTR	5	95_1200_woTR
6	126_500_tot	6	126_500_tot
7	126_500_woMR	7	126_500_woTR
8	126_500_woTR	8	126_1000_tot
9	126_1000_tot	9	126_1000_woTR
10	126_1000_woMR	10	126_1200_tot
11	126_1000_woTR	11	126_1200_woTR
		12 *	95_500_woTR
		13 *	95_1000_woTR
		14 *	126_500_tot

Table 2 presents the main psychoacoustic characteristics of the stimuli and the background noises. These metrics were calculated in MATLAB. The loudness metrics were calculated according to the standard ISO 532B [11] and the sharpness was weighted accordingly to the standard DIN 45692 [12]. The roughness was calculated with the Mosqito Python library [13].

Table 2: Psychoacoustic description of the stimuli (min and max of the set). The maximum given for *T2* excludes the 3 controls stimuli, otherwise max(*T2*) equals max(*T1*).

		L_{Amax}	L_{Aeq}	N5	D'L5 Children	D'L5 Road	S5	R5
T1	Min	41	34	3.0	21	17	1.2	0.03
	Max	54	43	8.3	41	32	1.6	0.12
T2	Min	33	26	1.2	24	11	1.1	0.02
	Max	47	35	4.6	34	25	1.5	0.12

As a reminder, the 5^{th} percentile (as for the loudness *N5*, the sharpness *S5* or the roughness *R5*) corresponds here to the value greater than 95% of the other values. The detectability level *D'L* quantifies the detectability by the bandwidth adjusted signal-to-noise ratio [7] such as:

$$D'L = 10\log_{10}\left(\frac{\eta\sqrt{\sum_{i=1}^{N}\Delta f_i\left(\frac{si}{ni}\right)^4}}{d'_{ref}}\right) \quad (1)$$

η: efficiency of a human detector (assumed 0.4 for a human observer),

Δf_i: bandwidth of the i^{th} one-third octave band,

s_i: sound pressure of the signal in the i^{th} one-third octave band,

n_i: sound pressure of the noise in the i^th^ one-third octave band,
$d'_{ref} = 1$.

2.2 Background noise

The background noises were chosen to be representative of an urban environment. One background noise, $Noise_{Road}$, is an extract of a steady traffic noise in which cars and motorcycles can be heard. There is no significant temporal variation and most of the energy is below 1000 Hz. The second background noise, $Noise_{Children}$, was recorded in a playground. It mainly contains noise from children playing with each other. This sound is much more variable both in the time and spectral domains. Punctually, some high frequency outbursts can be heard, when a child gets excited for example.
The sound level of both background noises has been fixed at 41.5 dB(A) L_{Aeq}. However, in Figure 1 one can notice that this does not imply an equal loudness. For example, the median loudness of $Noise_{Road}$ equals 2.5 sone against 1.6 sone for $Noise_{Children}$.

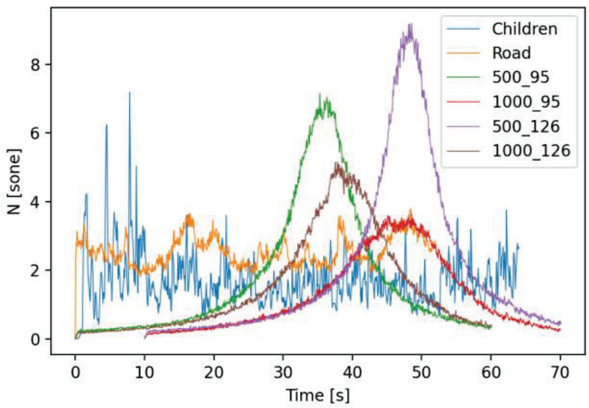

Figure 1: Loudness (ISO 532-1:2017, Mosqito) of the background noises and a selection of the stimuli played during *T1* described by their height and speed.

3. PSYCHOACOUSTIC TESTS

3.1 Listening room and equipment

The listening tests were performed in the listening laboratory of ONERA Chatillon with an 8.1 surround system composed of eight Focal Solo 6Be loudspeakers and a Focal Sub 6 subwoofer (cut-off frequency at 80 Hz). The room has de-parallelized walls and a reverberation time of 0.3 to 0.5 seconds. The environment is visually neutral, a chair and a computer are placed at the center of the room where the participant will carry out the listening test.
During the test, all the interactions with the participants (novels, questionnaire and collection of answers) are made through a graphic interface coded with MAX-MSP. The software also controls the reproduction of the background noises and plays the stimuli in a random order which is varied from one subject to the next.

3.2 Listening test protocols

The test consists of two identical sequences which only differ by the type of background noise ($Noise_{children}$ or $Noise_{road}$). During each sequence the background noise is played continuously.
The participants are asked to imagine themselves in an everyday-like situation: they are comfortably seated in their living room, reading for leisure some short stories that appear on the computer screen. Their window is open and overlooks a road/playground (depending on the background noise), from time to time a helicopter may fly over their neighborhood. Regardless of the noise, the participants can keep reading, they don't have to analyze the sound on the spot.
Each stimulus of 58 s is embedded in a 2 min background noise signal. After each signal, the participants have to answer two (*T1*) or three (*T2*) questions regarding the two last minutes. In both tests, the participants grade their feeling of comfort and the interference caused by the helicopter noise. The questions are presented in French but can be translated such as 'Imagine you are sitting outside, at a small table, drinking a cup of coffee. On the scale below, rate how annoyed/uncomfortable you would be. 1 = not annoyed at all, 6 = very annoyed' and 'Assess how the helicopter interfered with your reading. 1 = not at all, 6 = a lot.'. In *T2*, the participants are also asked if, yes or no, they heard a helicopter.
At the end of each sequence, the participants respond to a quick and simple reading test on the novels they have read and then take a five minutes break.

After the two sequences of the listening test, the participants' hearing is tested by a pseudo-audiogram to check if the participants are able to hear a sound as loud as the lower stimuli. Finally, they answer a short questionnaire to evaluate their noise sensitivity.

The only differences between *T1* and *T2* are that:

- Some stimuli have changed and most of the stimuli in *T2* are lower than the ones presented in *T1* (see 2.1*)*.
- In addition to the questions related to the annoyance a third question on the noticeability is added in *T2*. If the participants did not hear the helicopter, they do not answer the question about the interference caused by the stimuli. In this case the interference grade is recorded as '0'.
- In *T2*, the participants are told before the test that the number of helicopters is random so that there is not automatically one flyover between each questionnaire. This lie was made to avoid confirmation bias regarding the detection of the helicopter.

Both protocols were approved by the ethics committee of the University of Paris-Saclay (respectively n°CER-Paris-Saclay-2022-028 and n°CER-Paris-Saclay-2022-080). The tests were carried out in the spring of 2022 (*T1*) and during the winter of 2022/2023 (*T2*).

3.3 Participants

T1 participants were recruited by a subcontractor and paid small compensation. *T2* participants were volunteers mainly recruited among the ONERA's employees. The only selection criteria for participants was to not have no known untreated hearing problems. 34 subjects participated in *T1*. Among them, one participant was withdrawn from the results' analysis because he did not finish the test. The age of the participants was between 20 and 69 years old with a median of 38 years old. 14 of the 33 remaining subjects are male.

The results from 36 participants were analyzed for *T2* after one participant's answers were removed because the subject felt too cold to focus during the test. 24 participants were male. The participants' age ranged from 24 years to 69 years old with a median of 42 years old.

3.4 Statistical analysis

The results have been analyzed in R 4.2.1. The ANOVA analyses were done using the 'afex' version 1.2.1 and 'performance' 0.10.2 packages. When necessary, a Green-Geisser correction was applied to adjust for lack of sphericity. If the assumptions of the ANOVA were clearly not met, the Kruskal-Wallis test was done using 'rstatix' 0.7.1. The linear regressions used the *lm* function from 'stats' 4.2.1 and the multicollinearity checks were made with 'car' 3.1.1. Multilevel analyses were carried out thanks to the *lmer* function from 'lme4' 1.1.30.

4. RESULTS AND DISCUSSION

This paper focuses on the analysis of the interference at two different scales: the characteristics of the flyover (height, speed and signature) and the SQM characterizing the stimuli. The results on the noticeability and the comfort will be developed in another paper as will the use of multilevel analysis.

4.1 Different responses strategies

When analyzing the results of *T1,* it appeared that all the participants' answers could not be analyzed as one unique group because of the presence of two distinct response strategies. This distinction does not remain in *T2*.

The participants of *T1* can be separated into two subgroups of 16 and 17 participants. The ANOVA test shows that the subgroup 1 only based its ratings on the background noise ($p = .005$, $F(1, 13) = 11$, $\eta=0.13$) regardless of the stimuli ($p = .342$, $F(1.7, 48.2) = 1$). The subgroup 1 favors the background noise $Noise_{Road}$ against $Noise_{Children}$ with a consequent gap of two points between the two medians, see Figure 2. At the opposite, the subgroup 2 was not significantly affected by the background noise ($p = .221$, $F(1, 13) = 2$) but associated the interference to the different helicopter stimuli ($p < .001$, $F(5.1, 66.0) = 15$, $\eta=0.19$).

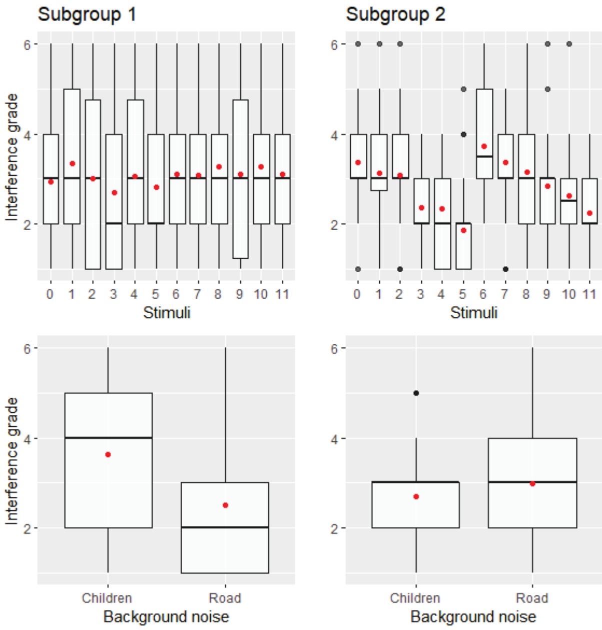

Figure 2: Grade of interference as function of the type of background noise or stimuli for the two subgroups of participants in *T1*.

There is not such a distinction between the participants in *T2*: all of them seem to consider both the background noise ($p < .001$, $F(1,30) = 28$, $\eta = 0.04$) and the stimuli ($p < .001$, $F(6.2,186.5) = 57$, $\eta = 0.36$) for their appreciation of the interference. As expected, because the sound power level of the stimuli was reduced, the grades are in average below the ones from *T1*, see Figure 3. The only exception comes from the three control stimuli '12', '13' and '14' to which the gain of *T1* had been applied.

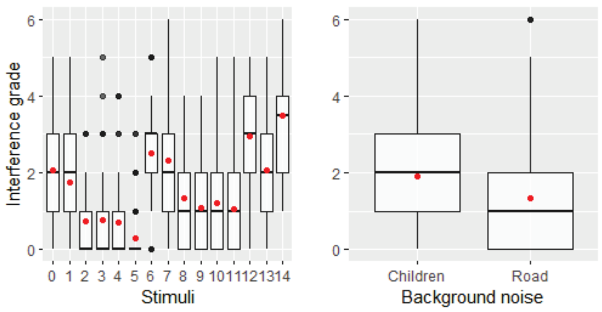

Figure 3: Grade of interference as function of the type of background noise or stimuli in *T2*.

Interestingly, there is also a significant interaction between the two ANOVA factors of background noise and stimuli ($p < .001$, $F(6.9,206.3) = 3.7$, $\eta = 0.03$). With $Noise_{Road}$ as a background noise, there is a bigger difference of interference between the 14 stimuli than with $Noise_{Children}$. Indeed, the quietest stimuli are more often not noticed above the road traffic and so the average interference grades are very low while the loudest stimuli obtain the same grade regardless of the background noise. As a result, there is a bigger difference between the interference caused by the stimuli when the cars are in the background.

4.2 Influence of the flyover characteristics

Because the analysis focuses on the stimuli, the subgroup 1 from *T1* will not be taken into account here. Moreover, in this section the three signals presented in *T2* with the gain applied in *T1* - the 'control stimuli'- will be removed from the dataset used for the ANOVA.

Referring to Table 1 and Figure 1, one can observe that the stimuli seem to be aggregated as a function of the height of the flyover: the higher the helicopter the lower the interference. Other boxplots (not shown here) suggest that the interference increases with the speed of the helicopter and that the signature without the tail rotor *woTR* is less annoying.

The ANOVA test carried out with the subgroup 2 from *T1* confirms these trends. The three parameters have a significant influence on the grading but the height has a bigger effect size η ($p < .001$, $F(1, 13) = 89$, $\eta = 0.14$) than the speed ($p = .001$, $F(1, 13) = 16$, $\eta = 0.02$) or the signature ($p = .002$, $F(1.4, 18.6) = 11$, $\eta = 0.03$).

A t-test enables to dissect the difference between the three signatures. For the subgroup 2, the participants were able to distinguish the three signatures and it significantly impacted their annoyance's rating. The difference between the total signature *tot* and the signature without the main rotor *woMR* has a p-value of 0.04, just below the 0.05 threshold. The difference between the total signature *tot* and the signature without the tail rotor *woTR* has a p-value lower than 0.001 and the difference between *woTR* and *woMR* is also significant with a p-value of 0.01. The ANOVA test also reveals a small interaction between the height and the signature ($p = .013$, $F(1.7, 22.7) = 6$, $\eta = 0.01$): at high height, the difference between the signature without the tail rotor *woTR* and the other signatures increases. Yet, these results should be mitigated in regard of the low effect size associated with the signature.

Because the answers from *T2* lean towards the lower values of interference, the normality of the distribution can be questioned. Because of the doubt on the normality assumption for the ANOVA analysis, a Kruskal-Wallis test was also performed on the three factors: height ($p < .001$, $\eta = 0.22$), speed ($p < .001$, $\eta = 0.04$) and signature ($p = .011$, $\eta = 0.001$). The results of the Kruskal-Wallis test are consistent with the ANOVA results for all the factors: the height ($p < .001$, $F(1.4, 42.0) = 98$, $\eta = 0.21$), the speed ($p < .001$, $F(1, 30) = 32$, $\eta = 0.05$) and the signature ($p = .001$, $F(1, 30) = 13$, $\eta = 0.01$). The findings are similar to the results from *T1*: the three factors are significant but the height is by far the most important one.

Taking a step back, one can see that the evolution of the interference through the three flight characteristics seems to follow the evolution of the stimuli sound level. Indeed, the interference increases with the speed, decreases with the height and is higher for the *tot* signature: overall the grades increase when the sound level rises. The stakes are now to understand how much variance is explained by the sound level and if other metrics contribute to the choices made by the participants.

4.3 Influence of the sound quality metrics

The analysis of the linear regressions allows to distinguish which metrics have an influence on the interference. The variance explained by each SQM is presented in Table 3 through the regression coefficients. It appears that among the several SQM tested, only the loudness and sound level indicators have an influence on annoyance. In both listening tests, the roughness has no impact on the interference. Regarding the sharpness, one can wonder if its results are not due to the correlation of the metric with the loudness ($r_{Pearson\ S5\_LN5} = 0.89$ in *T1* and $r_{Pearson\ S5\_LN5} = 0.90$ in *T2*).

It is interesting to note that the behaviors of the different metrics related to sound level or loudness (L_{Amax}, L_{Aeq}, LN5, SELA) are very similar and that in any case, the regression coefficients remain a bit low. This might be due to the fact that the protocol of the listening tests does not favor the concentration of the participants on the subtleties of each stimulus because: 1) the stimuli are played above a background noise 2) the participants are distracted by a reading activity 3) the participants are asked not to concentrate too much on the sounds, not more than in a real-life situation 4) the stimuli are long and vary over time.

Therefore, the linear regressions between the SQM -except the roughness- are significant but very weak, in particular for *T1*.

Table 3: Regression coefficients of the linear regressions between the interference and different SQM.

Metrics	r^2 *T1* subgroup2	r^2 *T2*
L_{Amax}	0.19	0.36
L_{Aeq}	0.19	0.35
LN5	0.19	0.36
S5	0.15	0.30
R5	0.02	0.01
D'L5	0.03	0.31
SELA	0.16	0.35

One can also note that the detectability level is well correlated with the interference in *T2* but not in *T1*. The choice of limiting the analysis of *T1* to the subgroup 2 (not influenced by the background noise) could explain that difference.

The low values of the regression coefficients of the linear regressions are also explained by the different notation corresponding to each participant. The multilevel analyses, which will be presented in another paper, allow to consider the fact that the answers are not strictly independent by grouping the results by participants (the assumption of independence of observations can be debated as the personality and background of the participants might have influence their gradings). The explained variance is then improved and the regression coefficients are above 0.50 both for *T1* and *T2*.

5. CONCLUSION

Two listening tests were designed to study the notions of annoyance and noticeability of helicopter noise considering two different background noises and a reading activity. The stimuli were synthetized and spatialized to represent realistic helicopter flyovers with different heights and speeds. Three different signatures were also studied to understand the impact of the main rotor and the tail rotor on the helicopter noise perception.

The statistical analysis focused on the annoyance and more specifically on the interference. It appeared that both the stimuli and the background noise have a significant influence on the grades given by the participants. Different strategies emerged and while in *T2* the two background noises were considered by all the participants in their grading, in *T1* the participants linked their perception either to the background noise or the helicopter noise. Regarding the impact of the stimuli on the annoyance, the interference increases strongly when the helicopter height diminishes.

This is explained by the fact that sound level or loudness are the most important indicators of the annoyance caused by the stimulus. Interestingly, there is no difference between sound level or loudness regression coefficients. They seem to equally explain the variance of annoyance. The roughness has no impact on the interference. Overall, the regression coefficients are quite low. This is partly due to the protocol of the listening test with the presence of a background noise as well as a reading activity. The notation also varies among the participants; multilevel analysis is an interesting method to quantify that and will be further developed in later publications.

6. ACKNOWLEDGMENTS

The authors are very grateful to the participants of the two listening tests of this study.

This work was carried out in the frame work of the MOTUS project, supported by the French Civil Aviation Agency (DGAC) under the French government plan 'Plan de Relance' and funded by the European Union via the Next generation EU plan.

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