Caractérisation physique et perceptive de différentes compositions de trafic routier urbain pour la détermination d'indicateurs de gêne en situation de mono-exposition et de multi-exposition

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"It ain't what you don't know
that gets you into trouble.
It's what you know for sure
that just ain't so."
Mark Twain

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Résumé

Le bruit de la circulation routière, et en particulier le bruit des deux-roues motorisés, constituent une importante source de gêne sonore. Afin d'estimer l'exposition sonore dans les villes de plus 100 000 habitants, la directive européenne 2002/49/CE impose la réalisation de cartes de bruit stratégiques, basées sur l'indice L_{den}. Cet indice est également utilisé dans des relations exposition-réponse, afin de prédire les pourcentages de personnes gênées, notamment par le bruit du trafic routier. En couplant les cartes de bruit stratégiques et ces relations exposition-réponse, des cartes de gêne pourraient être établies. Toutefois, la pertinence de cet indice pour prédire la gêne due au bruit en milieu urbain est souvent remise en cause, car de nombreux facteurs acoustiques influents (*e.g.* les caractéristiques spectrales et temporelles) ne sont pas pris en compte par cet indice. Cette thèse vise à améliorer la caractérisation de la gêne due au bruit de trafic routier urbain en considérant différentes compositions de trafic et la présence des deux-roues motorisés. Dans ce but, des expériences sont menées en conditions contrôlées. Une première étude a porté sur l'influence de plusieurs facteurs acoustiques relatifs aux périodes de calme et aux bruits de passage de véhicules sur la gêne due au bruit de trafic routier urbain. Cette étude a conclu à l'influence de la présence de périodes de calme et du nombre de véhicules au sein du trafic routier urbain et à l'absence d'influence de l'ordre des véhicules routiers, de la position et de la durée des périodes de calme. Ces résultats ont été utilisés afin de mener la caractérisation physique et perceptive de différentes compositions de trafic routier urbain. La régression multi-niveau a été utilisée pour calculer la gêne, en considérant 1) des facteurs acoustiques influents à l'aide de combinaisons pertinentes d'indices et 2) un facteur non acoustique : la sensibilité au bruit. Dans les villes, le bruit routier est souvent entendu en situation de multi-exposition avec d'autres bruits. Dans le cadre de ces travaux de thèse, les situations de multi-exposition aux bruits routier et d'avion ont été étudiées. Pour cela, un travail semblable à celui mené pour le bruit de trafic routier urbain a été mené pour le bruit d'avion conduisant également à des combinaisons pertinentes d'indices. En vue de caractériser les gênes dues aux bruits de trafic routier et d'avion pour des situations de multi-exposition sonore, les données des précédentes expériences ainsi que celles d'une expérience conduite en situation de multi-exposition à ces bruits combinés ont été utilisées au travers d'une régression multi-niveau adaptée, comme cela a pu être mené dans la littérature. La régression multi-niveau a ainsi permis la proposition de modèles de gêne pour chaque source de bruit. Puis, la gêne totale due à des situations de multi-exposition à ces bruits a été étudiée, afin de mettre en évidence les phénomènes perceptifs mis en jeu. Des modèles de gêne totale ont été proposés, en utilisant les modèles de gêne due à chaque source. Enfin, les modèles de gêne obtenus pour chaque source et les modèles de gêne totale ont été confrontés aux données d'une enquête socio-acoustique. A cet effet, une méthodologie a été proposée afin d'estimer les différents indices des modèles à partir des valeurs du L_{den}, issues de cartes de bruit et utilisées pour définir l'exposition au bruit des personnes enquêtées. Cette confrontation a montré que les modèles proposés à partir d'expériences menées en laboratoire et couplés à la méthodologie d'estimation des indices à partir des valeurs du L_{den} permettent une bonne prédiction de la gêne *in situ*.

Mots clés : gêne sonore de court-terme, gêne sonore de long-terme, bruit de trafic routier urbain, bruit d'avion, deux-roues motorisés, mono-exposition, périodes de calme,

sensibilité au bruit, multi-exposition sonore, gêne totale, expérience en laboratoire, environnement simulé, enquête socio-acoustique.

Abstract

Road traffic noise, and in particular powered two-wheeler noise, constitute an important source of noise annoyance. In order to estimate the noise exposure in cities of more than 100 000 inhabitants, the European directive 2002/49/EC requires the elaboration of strategic noise maps, based on the L_{den} index. This index is also used in exposure-response relationships, to predict the percentages of annoyed people, by road traffic noise for example. By coupling strategic noise maps and these exposure-response relationships, noise annoyance maps could be established. The relevance of this index to predict noise annoyance in cities is however often questioned, since many influential acoustical factors (*e.g.* spectral and temporal features) are not considered by this index. The aim of this thesis is to enhance the characterization of noise annoyance due to different compositions of urban road traffic including powered two-wheelers. To achieve this goal, experiments were carried out under controlled conditions. A first study concerned the influence of several acoustical features related to quiet periods and vehicle pass-by noises on the annoyance due to urban road traffic noise. This study demonstrated the influence of the presence of quiet periods and of the number of vehicles within the urban road traffic and to the absence of the influence of the order of the vehicle pass-by noises, the position and duration of quiet periods. These results were used to carry out the physical and perceptual characterization of different compositions of urban road traffic noise. Multilevel regression was used to calculate noise annoyance, by coupling combinations of indices relating to influential acoustical features and an individual factor: noise sensitivity. In cities, road traffic noise is often combined with other noises. In the framework of this thesis, noise exposure to road traffic noise combined with aircraft noise was studied. Therefore, the same work as the one performed for urban road traffic noise was carried out for aircraft noise, leading also to relevant combinations of noise indices. In order to characterize annoyances due to road traffic noise and to aircraft noise in a combined exposure situation, data from the previous experiments and from an experiment dealing with these combined noises were used through an appropriate multilevel regression, as done in literature. The regression allows annoyance models for each noise source to be proposed. Then, total annoyance due to combined noises was studied, in order to highlight the perceptual phenomena related to the combined exposure. Total noise annoyance models were proposed, using proposed annoyance model of each noise source. Finally, these single source annoyance models and total annoyance models were tested using data of a socio-acoustic survey. To do this, a methodology has been proposed to estimate the different indices involved in the annoyance models, from the L_{den} values obtained from the strategic noise maps and used to define the noise exposure of the respondents. This confrontation showed that the models proposed on the basis of experiments carried out under laboratory conditions and coupled with a methodology of estimation of the noise indices from L_{den} values, enabled a good prediction

of *in situ* annoyance.

Keywords: Short-term noise annoyance, long-term noise annoyance, urban road traffic noise, aircraft noise, powered-two-wheeler, single exposure, quiet period, noise sensitivity, combined exposure, total annoyance, experiment under laboratory conditions, simulated environment, socio-acoustic survey.

Table des matières

Liste des tableaux

Table des figures

Introduction

Le bruit est un problème environnemental majeur dans les zones urbaines, pour lequel l'exposition continue de croître, contrairement à d'autres sources de pollutions environnementales [138]. En effet, compte tenu de la densification des zones urbaines et malgré les règlementations adoptées pour gérer l'exposition sonore (*e.g.* [18, 19, 70]), de plus en plus de personnes sont exposées aux bruits (*e.g.* des transports, industriel, de chantier, de voisinage). Or, de nombreuses études ont montré l'impact du bruit sur la santé, définie par l'Organisation Mondiale de la Santé (OMS) comme un état complet de bien-être physique, mental et social [138]. L'exposition au bruit peut entrainer par exemple des maladies cardiovasculaires, la perturbation du sommeil, des acouphènes, etc. [1]. L'OMS estime ainsi que le bruit est responsable de la perte annuelle d'un million d'années en bonne santé en Europe [138]. L'un des principaux effets de l'exposition au bruit sur la santé est la gêne sonore. Ainsi, une enquête menée sur la qualité de l'environnement auprès des ménages français a montré que la gêne due au bruit est la nuisance la plus fréquemment citée devant la pollution atmosphérique et les problèmes d'insécurité [24]. Cette gêne sonore est principalement due aux bruits de transports (*e.g.* [24, 50]), parmi lesquels le bruit de la circulation routière et le bruit des deux-roues motorisés, sources acoustiques associées à des comportements, constituent les nuisances les plus citées [50]. Alors que le bruit du trafic routier est la source la plus gênante en termes de pourcentages de personnes concernées, le bruit du trafic aérien est la source la plus gênante en termes de pourcentages de personnes exposées à un niveau donné [82]. De plus, bien que les avions soient moins bruyants que par le passé, l'augmentation du trafic aérien ne permet pas une diminution de l'exposition au bruit [23].

Afin d'améliorer la gestion de l'exposition au bruit, le Parlement Européen et le Conseil de l'Union Européenne ont adopté en 2002 la directive 2002/49/CE [70], relative à l'évaluation et à la gestion du bruit dans l'environnement. Cette directive impose la réalisation de cartes de bruit stratégiques aux agglomérations de plus de 100 000 habitants, aux grands axes de transport et aux grands aéroports. Ces cartes doivent être réalisées séparément pour les bruits du trafic routier, du trafic ferroviaire, du trafic aérien et des activités industrielles. Elles représentent l'exposition au bruit sur une zone donnée par la modélisation de l'indice L_{den} – niveau jour-soir-nuit. Cet indice rend compte d'une exposition sonore moyenne, pénalisée en fonction du moment de la journée afin de tenir compte de la perturbation du sommeil par le bruit la nuit et de la gêne plus importante le soir par rapport à la journée. Par ailleurs, pour chaque source de bruit, des relations exposition-réponse expriment les pourcentages de personnes exprimant un certain niveau de gêne en fonction de l'indice L_{den} [82, 85]. En couplant ces relations exposition-réponse aux cartes de bruit stratégiques, ces dernières pourraient donc être interprétées comme des cartes de gêne. Cependant, plusieurs limites de ces relations exposition-réponses et des cartes de bruit remettent en cause une telle utilisation. Ainsi, une étude récente portant sur la gêne en situation de multi-exposition aux bruits de transport a montré que ces relations exposition-réponse permettaient de prédire correctement uniquement le pourcentage de personnes très gênées par le bruit du trafic routier [42], mais ne permettaient pas de prédire les pourcentages de personnes gênées et peu gênées par le bruit du trafic routier ni les différents pourcentages de personnes très gênées, gênées et peu gênées par les bruits de train et d'avion. Par ailleurs, pour les cartes de bruit stratégiques du trafic routier élaborées jusqu'à ce jour, les deux-roues motorisés sont assimilés aux véhicules légers. L'augmentation de leur usage [72] n'est donc pas considérée lors de l'élaboration des cartes de bruit, bien qu'ils soient connus pour être particulièrement gênants (*e.g.* [50, 103]). Cette lacune sera corrigée pour les échéances d'élaboration des cartes de bruit après 2022, puisqu'une catégorie spécifique aux deux-roues est introduite dans la révision de la directive européenne [33]. Cependant, des sensations particulièrement prégnantes pour la gêne des deux-roues motorisés, comme les sensations de modulation (*e.g.* [61, 103, 137]) ne seront toujours pas prises en compte. En effet, les indices énergétiques, comme le L_{den}, permettent de considérer le seul niveau sonore moyenné des sources acoustiques alors que d'autres caractéristiques acoustiques telles que le contenu spectral, les variations irrégulières de l'amplitude, les sensations de modulation, sont connues pour influencer également la gêne sonore (*e.g.* [2, 30, 58, 69, 130, 131]). De plus, de nombreuses études ont montré l'influence des facteurs non-acoustiques sur les effets sanitaires du bruit (*e.g.* [40, 100]), en particulier sur la gêne sonore (*e.g.* [125, 62, 65, 97]). Des modèles prédictifs de gêne ont donc été proposés, en considérant des facteurs acoustiques et non-acoustiques (*e.g.* pour le bruit du tramway [117, 130, 131], pour le bruit d'avion [84, 5]). Afin d'améliorer la prédiction de la gêne pour les différentes sources de bruit, il est donc nécessaire de mieux caractériser les sensations acoustiques gênantes de chaque source de bruit par des indices appropriés et d'intégrer ces indices acoustiques et des facteurs non-acoustiques dans les modèles de gêne. Enfin, les situations de multi-exposition sonore sont de plus en plus fréquentes [79]. Or, dans ces situations, les bruits des sources en présence interagissent [91, 124, 136], ce qui rend difficile leur caractérisation et donc la modélisation de la gêne sonore. Par conséquent, il n'existe pas actuellement de consensus scientifique pour un modèle de gêne pour les situations de multi-exposition. Afin d'améliorer la prédiction de la gêne due à ces situations, il est donc nécessaire de mieux comprendre les interactions entre les bruits des différentes sources et de proposer des modèles adaptés à ces situations.

Démarche et organisation du document

Cette thèse s'inscrit dans une démarche de contribution à l'amélioration des indicateurs de gêne, en vue d'une utilisation future à partir des cartes de bruit, pour le bruit de différentes compositions du trafic routier urbain, entendu seul et en présence de bruit aérien. Cette thèse s'inscrit ainsi dans la continuité des travaux de thèse de J. Morel [87] et d'A. Klein [60], qui se sont attachés à proposer des indicateurs de gêne pour les bruits de passage de véhicules routiers urbains. Cette thèse utilisera ainsi les enregistrements et les résultats de ces travaux afin d'étudier la gêne due à différentes compositions de trafic routier urbain. La première étape de ces travaux de thèse consiste donc à identifier les caractéristiques acoustiques des bruits de trafic routier urbain et d'avion qui influencent la gêne sonore. Dans un deuxième temps, des indices sont proposés pour rendre compte de ces caractéristiques acoustiques et la régression multi-niveau, considérant des facteurs acoustiques et non-acoustiques, est utilisée pour calculer la gêne due à chaque bruit. Puis, les phénomènes perceptifs mis en jeu lors des situations de multi-exposition aux bruits de trafic routier urbain et d'avion sont identifiés et différents modèles de gêne due à ces situations sont construits en laboratoire. Enfin, la confrontation de ces modèles à des données de gêne mesurées lors d'une enquête socio-acoustique a été menée en proposant une méthode d'estimation des différents indices à partir des valeurs de l'indice L_{den} issues des cartes de bruit stratégiques.

L'organisation de ce document est présentée ci-après en donnant brièvement le contenu de chaque chapitre constituant les étapes de ces travaux. Les questions scientifiques traitées seront introduites en détail au début de chaque chapitre.

Le Chapitre 1 dresse un état de l'art de la gêne sonore due au bruit du trafic routier et au bruit d'avion. Dans un premier temps, la gêne en situation de mono-exposition à chacun de ces bruits est étudiée. Puis, les phénomènes perceptifs qui peuvent avoir lieu dans les situations de multi-exposition en général sont présentés, ainsi que les modèles de gêne totale de la littérature qui tiennent compte de ces phénomènes. Enfin, la gêne totale due aux bruits de trafic routier et d'avion est étudiée.

Le Chapitre 2 présente l'étude des facteurs non-acoustiques influant la gêne due au bruit de trafic routier, la gêne due au bruit d'avion et la gêne totale due à ces deux sources de bruit combinées. Pour cela, les données d'une enquête socio-acoustique, conduite par une équipe pluridisciplinaire [31], sont utilisées et conduisent à la prise en compte d'un facteur non-acoustique, la sensibilité au bruit, dans la suite de ces travaux.

Le Chapitre 3 étudie l'influence sur la gêne sonore de facteurs acoustiques relatifs aux périodes de calme et aux bruits de passage de véhicules routiers urbains. Pour cela, des séquences sonores ont été construites à partir d'enregistrements *in situ* et évaluées en laboratoire, du point de vue de la gêne sonore. Cette étape préliminaire est nécessaire pour évaluer l'influence potentielle de paramètres de construction de séquences sonores de trafic routier urbain sur la gêne de court terme, évaluée en conditions contrôlées.

Le Chapitre 4 présente la caractérisation physique et perceptive de différentes compositions de trafic routier urbain. À partir des enregistrements *in situ* et des résultats du Chapitre 3, des séquences sonores de différentes compositions de trafic routier sont construites et évaluées en laboratoire du point de vue de la gêne sonore. Les résultats d'une tâche de verbalisation libre aident à l'identification de caractéristiques acoustiques influant la gêne sonore. La régression multi-niveau, intégrant des facteurs non-acoustique et acoustiques, est utilisée afin de calculer la gêne due à ces séquences sonores.

Le Chapitre 5 présente la caractérisation physique et perceptive de bruits d'avions. À partir d'enregistrements *in situ*, la gêne due au bruit d'avion est évaluée en laboratoire. Les résultats d'une tâche de verbalisation libre aident à l'identification de caractéristiques acoustiques influant la gêne sonore. La régression multi-niveau, intégrant des facteurs non-acoustique et acoustiques, est utilisée afin de calculer la gêne due à ces séquences sonores.

Le Chapitre 6 présente la caractérisation physique et perceptive de bruits combinés de trafic routier urbain et d'avion. À partir des séquences sonores précédemment évaluées, des séquences sonores combinant ces deux bruits sont construites. La gêne due à chaque source et la gêne due à la combinaison des deux bruits sont évaluées en conditions contrôlées. Différents modèles de gêne pour chaque source sont considérés. La gêne totale due à la combinaison de ces bruits est ensuite étudiée, afin de mettre en évidence les phénomènes perceptifs liés à la combinaison des bruits. Puis, des modèles de gêne totale sont proposés, sur la base des modèles de gêne pour chaque source précédemment établis. Enfin, une méthodologie est proposée afin d'estimer les différents indices impliqués dans les modèles à partir des valeurs du L_{den} issues des cartes de bruit stratégiques et permet ainsi de confronter les modèles de gêne de chaque source et de gêne totale aux données de l'enquête socio-acoustique présentée au Chapitre 2.

Enfin, les principales conclusions et perspectives de ce travail de thèse sont données en fin de document.

Chapitre 1

État de l'art : la gêne sonore en situation de mono-exposition et de multi-exposition à des bruits de trafic routier et d'avion

Ce chapitre aborde de façon synthétique en renvoyant à des états de l'art plus documentés : i) les sources de bruit étudiées dans ces travaux de thèse, ii) la gêne sonore et les principaux indices apparaissant comme prometteurs dans la littérature pour caractériser la gêne en situation de mono-exposition sonore et iii) la gêne en situation de multi-exposition et ses principaux modèles.

1 Les sources de bruit

Dans cette section, les sources des bruits de trafic routier et d'avion sont présentées brièvement. Pour plus de détails, le lecteur pourra se référer à la thèse de J. Morel [87] pour le bruit de trafic routier urbain et à la thèse de B. Barbot [3] pour le bruit d'avion.

1.1 Le bruit du trafic routier

Le bruit émis par les infrastructures routières dépend de plusieurs facteurs :
- le trafic routier (c'est-à-dire à la fois la composition et le débit),
- la vitesse,
- l'allure des véhicules (c'est-à-dire accélérée, décélérée ou vitesse constante),
- la rampe ou le profil en long de la route,
- et la nature du revêtement de chaussée.

La Nouvelle Méthode de Prévision du Bruit (dite NMPB) est utilisée pour la réalisation des cartes de bruit, conformément à la directive européenne 2002/49/CE [70]. En ce qui concerne les sources de bruit, deux composantes principales sont considérées :
- la composante roulement, supposée émise par le contact pneumatique-chaussée, elle dépend de la vitesse et de la nature du revêtement et prédomine à hautes vitesses (classiquement, sur les voies rapides, départementales, etc.) ;

– et la composante moteur, supposée émise par l'ensemble des sources mécaniques du véhicule (principalement, par le groupe moto-propulseur, mais aussi par les bouches d'admission et d'échappement, par les engrenages, etc.), elle dépend de la vitesse, de la déclivité de la route et de l'accélération et prédomine à basses vitesses (classiquement, en milieu urbain).

Les paramètres influant l'émission sonore étant nombreux et les données parfois non-disponibles, certaines simplifications sont apportées par la NMPB. Ainsi, pour les données de trafic, seules deux catégories de véhicules (et donc deux spectres d'émission) sont considérées : les véhicules légers dont le Poids Total Autorisé en Charge (PTAC) est inférieur à 3,5 tonnes et les poids lourds dont le PTAC est supérieur à 3,5 tonnes. Ainsi, les deux-roues motorisés ne sont pas pris en compte de façon spécifique, mais assimilés aux véhicules légers, alors que de nombreux travaux ont mis en évidence l'importance des deux-roues motorisés dans la gêne due au bruit de trafic routier (*e.g.* [87, 103, 137]). Cette simplification était considérée comme acceptable, compte tenu de la faible proportion de deux-roues motorisés dans le trafic total. Or, cette proportion est en augmentation [72], rendant cette simplification plus discutable. De même, tous les véhicules dont le PTAC dépasse 3,5 tonnes sont agrégés, alors que les véhicules de cette catégorie sont très différents (*i.e.* les bus, les camions à 2, 3 ou 4 essieux, voire plus). Le spectre d'émission moyen considéré correspond à un poids-lourds avec au moins 4 essieux.

Compte tenu des incertitudes de cette méthode et des progrès techniques qui permettent le recueil de plus de données, une méthode d'évaluation commune du bruit [33] a été proposée en 2015 pour les prochaines échéances de la directive européenne [70]. Cette méthode considère notamment plus de catégories de véhicules routiers :

– les véhicules légers, c'est-à-dire les moins de 3,5 tonnes,
– les poids-lourds moyens, c'est-à-dire les véhicules de plus de 3,5 tonnes avec 2 essieux,
– les poids-lourds, c'est-à-dire les véhicules qui ont plus de 2 essieux,
– et les deux-roues motorisés.

Une catégorie ouverte a été prévue dans la méthode d'évaluation commune du bruit [33]. Cette catégorie sera à définir en fonction des développements de nouveaux moyens de transports, qui seraient suffisamment différents des autres catégories de véhicules pour nécessiter une catégorie particulière (*e.g.* véhicule électrique ou hybride).

1.2 Le bruit d'avion

Le bruit émis par un avion peut se diviser en deux composantes principales [86] : le bruit aérodynamique et le bruit moteur. Le bruit aérodynamique est dû aux turbulences aérodynamiques créées autour de l'avion (*cf.* Figure 1.1 pour les principales sources de bruit aérodynamique). Ce bruit domine en phase d'approche.

Le bruit moteur a quant à lui plusieurs origines [86], notamment, les turbulences en sortie de tuyère (*cf.* Figure 1.2, qui créent le bruit dit de jet), le mouvement des soufflantes, du compresseur et de la turbine (*i.e.* les parties tournantes), les turbulences créées par le mouvement des aubes lorsque la vitesse de leur extrémité devient supersonique (effet appelé "buzz-saw" dans [3]) ainsi que la combustion du kérosène (qui crée le bruit dit de combustion).

La Figure 1.3 présente un spectrogramme typique d'un bruit d'avion, mesuré durant un décollage. Ce spectrogramme présente l'évolution au cours du temps de la distribution

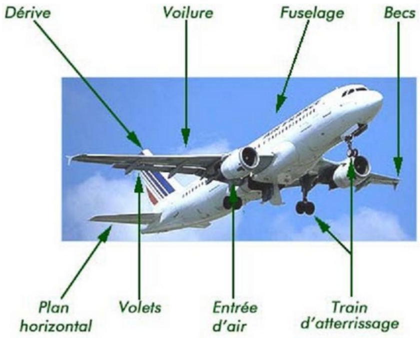

Figure 1.1 – Principales sources du bruit aérodynamique. Source : DGAC [27].

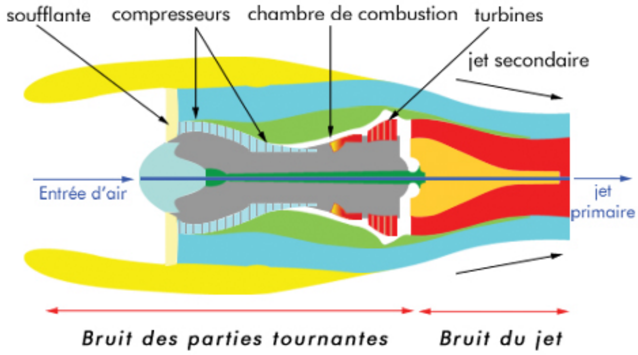

Figure 1.2 – Coupe d'un réacteur à double flux. Source : DGAC [27].

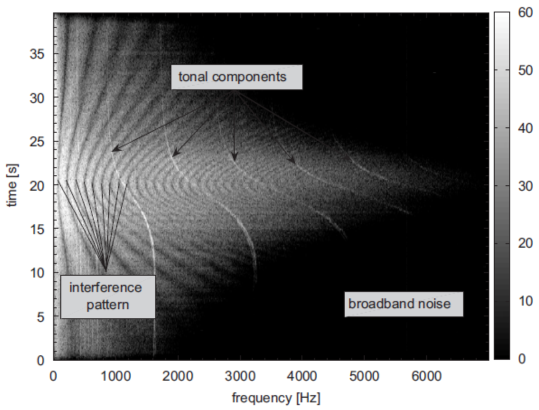

Figure 1.3 – Spectrogramme d'un bruit d'avion mesuré durant un décollage (niveau de pression sonore en dB). Source : Figure 3 de Berckmans *et al.* [8].

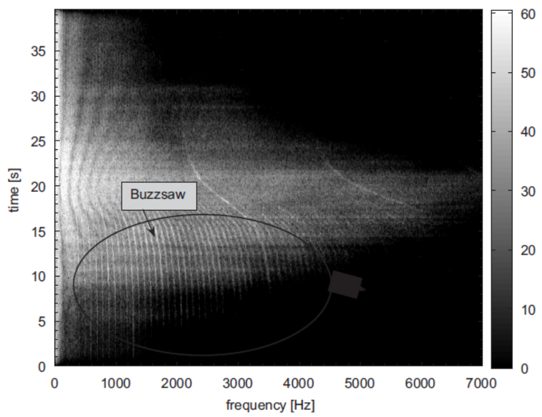

Figure 1.4 – Spectrogramme montrant un effet "buzz saw" (niveau de pression sonore en dB). Source : Figure 5 de Berckmans *et al.* [8].

de l'énergie par fréquence. La figure révèle trois composantes principales : des composantes tonales ("tonal components", dues au bruit des parties tournantes et à certains bruits aérodynamiques), un bruit large bande ("broadband noise", dû au bruit de combustion, au bruit de jet et à certains bruits aérodynamiques) et des interférences ("interference pattern", dues aux interférences entre le bruit direct et le bruit réfléchi par le sol). L'effet "buzz-saw" est identifié sur la Figure 1.4 et se caractérise par un ensemble de raies spectrales, très proches les unes des autres.

2 La gêne sonore

Les effets du bruit sur la santé, qu'ils soient acoustiques (*e.g.* perte d'audition) ou extra-auditifs (*e.g.* gêne, perturbation du sommeil, maladies cardio-vasculaires), sont nombreux et ont été largement étudiés (*e.g.* [1]). Cependant, les personnes exposées au bruit se plaignent principalement de la gêne occasionnée, sans mentionner d'autres effets sanitaires dus au bruit, bien que certaines études basées sur la modélisation en équations structurelles aient montré l'influence de la gêne sonore sur les effets sanitaires (*e.g.* la perturbation du sommeil [11, 40]).

2.1 Définition de la gêne

L'Organisation Mondiale de la Santé définit la santé ainsi : "la santé est un état de complet bien-être physique, mental et social, et ne consiste pas seulement en une absence de maladie ou d'infirmité"[1]. La gêne est ainsi l'une des 5 maladies liées au bruit pour lesquelles le nombre d'années en bonne santé perdues annuellement a été estimé [138].

Guski *et al.* [46] ont mené une étude sur la définition de la gêne en interrogeant des experts de différentes nationalités et de différentes langues maternelles. Il apparait que la gêne est un concept multi-facettes qui couvre à la fois les réactions immédiates aux bruits (ex : le dérangement ou la perturbation des activités) ainsi que les jugements du bruit (ex : la nuisance, le déplaisir ou l'énervement). Guski *et al.* [46] proposent ainsi une définition de la gêne : *"La gêne est un concept psychologique qui décrit une relation entre une situation acoustique et une personne qui est forcée par le bruit de faire quelque chose qu'il/elle ne veut pas faire, qui cognitivement et émotionnellement évalue cette situation et se sent en partie désemparé."*[2]

Lors des études portant sur la gêne sonore, deux types de gêne peuvent être évalués : la gêne de court-terme et la gêne de long-terme. **La gêne de court-terme** est généralement évaluée en laboratoire. Une mise en situation (complètement imaginaire ou aidée en environnement simulé) est proposée aux participants. Ces derniers doivent alors évaluer la gêne ressentie en s'imaginant chez eux, exposés au bruit. **La gêne de long-terme** est généralement évaluée lors des enquêtes, au domicile des personnes interrogées. Il leur est alors demandé d'effectuer un jugement rétrospectif sur une période assez longue : ainsi, Fields *et al.* [37] recommandent une évaluation de la gêne sur les 12 derniers mois.

2.2 Les facteurs influant la gêne

La gêne lie une source à un auditeur. Les facteurs qui influencent la gêne sont donc nombreux, certains relatifs à l'auditeur, son logement et son environnement en général (facteurs dits non-acoustiques), d'autres à la source au bruit (facteurs dits acoustiques).

2.2.1 Les facteurs non-acoustiques

Les facteurs non-acoustiques se divisent en trois catégories [36, 77] :
- les facteurs démographiques (*e.g.* âge, sexe, statut marital, catégorie socio-professionnelle) ;
- les facteurs d'attitude (*e.g.* la crainte de la source de bruit, la sensibilité au bruit) ;
- les facteurs situationnels (*e.g.* le temps passé au domicile, l'isolation acoustique du domicile, l'orientation du domicile).

1. Préambule à la Constitution de l'Organisation Mondiale de la Santé, tel qu'adopté par la Conférence internationale sur la Santé, New York, 19-22 juin 1946 ; signé le 22 juillet 1946 par les représentants de 61 États. 1946 ; (Actes officiels de l'Organisation mondiale de la Santé, n^o. 2, p. 100) et entré en vigueur le 7 avril 1948.

2. "Noise annoyance is a psychological concept which describes a relation between an acoustic situation and a person who is forced to do things he/she does not want to do, who cognitively and emotionally evaluates this situation and feels partly helpless."

Diverses études ont étudié l'influence de ces facteurs sur la gêne sonore. Ainsi, d'après Langdon [68] pour le bruit de trafic routier, la sensibilité au bruit explique plus de variance dans les réponses de gêne que le niveau sonore. En ce qui concerne les bruits de transport et les bruits impulsionnels, Job [57] a retrouvé ce résultat, à la fois pour la sensibilité au bruit, mais aussi pour l'attitude par rapport à la source. Fields [36] a quant à lui montré que les facteurs d'attitude et l'isolation acoustique du logement influencent la gêne sonore, contrairement aux facteurs démographiques. Ces résultats rejoignent partiellement ceux de Miedema et Vos [83]. En effet, ils ont montré que la peur de la source et la sensibilité au bruit ont une influence sur la gêne sonore plus importante que les facteurs démographiques. Ainsi, alors que le sexe n'a pas d'influence, la gêne sonore est influencée par l'âge, résultat confirmé par Van Gerven *et al.* [132] qui ont montré que les personnes de 40-50 ans expriment une gêne plus importante que les autres. Paunović *et al.* [102] ont quant à eux montré un effet de l'orientation de la chambre par rapport à la rue. Enfin, en ce qui concerne la gêne due au bruit d'avion, Schreckenberg et Schuemer [120] ont montré que l'attitude par rapport à la source et par rapport aux autorités ont un effet important sur la gêne sonore, confirmant des résultats mis en évidence dans la littérature (*cf.* [77]).

2.2.2 Les facteurs acoustiques du bruit de trafic routier

Compte tenu de la variabilité des véhicules routiers et des trafics, de nombreux travaux se sont attachés à améliorer la prédiction de la gêne due au bruit de trafic routier. Ces travaux ont permis de mettre en évidence l'influence de certaines caractéristiques acoustiques sur la gêne sonore.

Ainsi, de nombreux travaux ont montré l'influence de l'intensité sonore et se sont attachés à proposer des indices pertinents pour la caractériser (*e.g.* [67, 112, 58]). Cependant, à partir d'une compilation d'enquêtes menées au sein de différents pays avec des protocoles différents, Job [57] a établi que les indices relatifs à l'intensité sonore ne permettent d'expliquer au mieux que 30% des variations observées dans les jugements de gêne. D'autres études ont également montré un résultat similaire (*e.g.* [9, 106, 105]). Ces résultats montrent que la gêne due au bruit de trafic routier ne peut pas être prédite uniquement à partir des indices énergétiques : d'autres facteurs influencent la gêne sonore.

En ce qui concerne les caractéristiques du trafic routier, plusieurs études se sont intéressées à l'influence de sa composition. Ainsi, Langdon [68] a montré que, pour les situations *in situ* où le trafic routier est pulsé (c'est-à-dire en présence d'intersection ou de congestion), les indices énergétiques ne permettent pas une prédiction précise de la nuisance sonore, contrairement au logarithme du nombre de poids-lourds. Labiale [64] a retrouvé en laboratoire l'influence à la fois de l'intensité sonore et du logarithme du nombre de poids-lourds. Björkman [15] a quant à lui montré que la gêne sonore augmente avec le nombre de poids-lourds, jusqu'à un point d'inflexion à partir duquel la gêne n'augmente plus. Les événements particulièrement bruyants ou remarquables ont également un effet sur la gêne sonore. Ainsi, Sato *et al.* [119] ont montré que le niveau sonore maximal permet une meilleure prédiction de la gêne sonore que le nombre de véhicules. De Muer *et al.* [26] ont quant à eux proposé un modèle de gêne basé sur les événements remarqués, qui améliore légèrement la prédiction de la gêne par rapport à l'emploi d'un indice énergétique seul.

En ce qui concerne les caractéristiques temporelles du bruit de trafic routier, plusieurs études ont montré l'importance de caractériser les variations temporelles irrégulières de l'amplitude (*e.g.* [112, 139]) ainsi que les variations régulières de l'amplitude (*e.g.* [137, 91]). Ainsi, Rasmussen [112] a montré que pour les bruits avec un important bruit de fond, un indice rendant compte à la fois de l'intensité sonore et de ses variations temporelles irrégulières est significativement corrélé à la gêne sonore et permet une meilleure prédiction de la gêne sonore qu'un indice énergétique seul. De plus, certaines études ont évalué l'influence des modulations d'amplitude sur la gêne sonore due au bruit de trafic routier urbain. Ainsi, pour les bruits de passage de véhicules routiers urbains, les indices psychoacoustiques de rugosité et de force de fluctuation ne sont que partiellement corrélés à la gêne sonore (*e.g.* [103, 61, 91]). Paviotti et Vogiatzis [103] ont montré que les modulations d'amplitude présentes dans les bruits de passage de deux-roues motorisés peuvent influencer la gêne sonore et que l'indice de rugosité seul ne permet pas de prédire de manière satisfaisante la gêne sonore due aux deux-roues motorisés. Klein *et al.* [61] ont donc développé des indices pour caractériser le caractère "pétaradant" et le caractère "nasal" des bruits de deux-roues motorisés, qui se sont avérés significativement corrélés avec la gêne sonore due à ces bruits de passage.

Le contenu spectral est également un facteur influant la gêne sonore. Ainsi, Jakovljević *et al.* [56] ont observé que les habitants de Belgrade sont plus gênés par le bruit de trafic routier que ne le prédisent les relations exposition-réponse de Miedema et Oudshoorn [82] et expliquent ce résultat par la présence de nombreux poids-lourds à Belgrade, ce qui génère des basses fréquences, ressenties plus gênantes que les moyennes et hautes fréquences (d'après Leventhall [73], cité dans [56]). Morel *et al.* [91] ont étudié la gêne sonore due à des bruits de passage de véhicules routiers urbains et ont proposé d'utiliser la sonie spécifique intégrée entre 15 et 18 Barks afin de tenir compte des hautes fréquences qui influencent la gêne sonore due aux bruits de deux-roues motorisés en accélération. Klein *et al.* [61] ont quant à eux proposé d'utiliser l'énergie totale des composantes tonales entre 16 et 24 Barks pour tenir compte des hautes fréquences qui influencent la gêne sonore due aux bruits de véhicules routiers urbains.

Compte tenu que plusieurs facteurs acoustiques contribuent à la gêne sonore, plusieurs auteurs ont proposé des modèles de gêne en combinant plusieurs indices (*e.g.* [34, 61, 91]). Ainsi, Fastl et Zwicker [34] ont proposé un indicateur de gêne qui considère à la fois l'intensité sonore perçue, le contenu spectral et les modulations d'amplitude. Cet indicateur s'est avéré pertinent pour caractériser la gêne due à des bruits de passage de véhicules légers, à différentes allures et différentes vitesses [34] mais pas pour caractériser la gêne due à des bruits de trafic [58].

2.2.3 Les facteurs acoustiques du bruit d'avion

Plusieurs facteurs acoustiques influencent la gêne sonore due au bruit d'avion. Ainsi, l'intensité sonore et le nombre d'événements sont deux importants facteurs influant la gêne sonore. Plusieurs études se sont attachés à étudier l'influence de ces deux facteurs. Powell [110] a étudié la gêne sonore en laboratoire pour des séquences de 30 minutes. Il a observé que la gêne sonore augmente avec le niveau sonore et le nombre d'avions. De même que Björkman [15] a montré que la gêne due au bruit routier augmente avec le nombre de poids-lourds jusqu'à un point d'inflexion, Powell [110] a montré que la gêne due au bruit d'avion augmente avec le nombre d'avion, jusqu'à un point d'inflexion dépendant du niveau sonore. Ainsi, la correction du niveau sonore à apporter pour rendre compte du nombre d'avions dépend du niveau sonore et est comprise entre 4 et 6 dB par doublement du nombre d'avions. L'impact du nombre d'avions est donc légèrement plus élevé que l'impact de l'énergie acoustique. Ce résultat a été retrouvé par Vogt [135].

Rylander et Björkman [114] ont quant à eux étudié la gêne sonore à proximité de petits aéroports, c'est-à-dire avec moins de 70 évènements par 24 h dont le niveau sonore équivalent est supérieur à 70 dB(A). Contrairement à de précédents résultats établis pour de plus grands aéroports [115], le niveau sonore maximal (défini par les auteurs comme étant la valeur maximale de niveau sonore équivalent pondéré A d'un seul bruit d'avion, se produisant au moins 3 fois par 24 h) n'a pas d'influence sur la gêne sonore. Rylander et Björkman [114] supposent donc que le niveau sonore maximal a moins d'influence sur la gêne sonore quand le nombre d'avions est faible par rapport aux situations où le nombre d'avions est élevé. Compte tenu de l'influence conjointe du niveau sonore et du nombre d'avions, plusieurs auteurs utilisent des indicateurs couplés (*e.g.* [110, 74]).

Afin d'étudier les dimensions acoustiques pertinentes dans la représentation perceptive des bruits d'avion, Barbot *et al.* [3] ont réalisé un test de préférence. Trois caractéristiques acoustiques ont ainsi émergé des adjectifs descriptifs donnés par les participants pour justifier leur préférence : le timbre, la répartition temporelle et l'intensité sonore. Ainsi, d'après Bauer *et al.* [6], le stress acoustique à l'origine de la gêne sonore est une variable complexe, pour laquelle le niveau de pression acoustique, mais aussi la composition temporelle et spectrale jouent un rôle décisif. Ils ont observé que les facteurs qui déterminent le plus la gêne sonore mesurée toutes les heures à proximité des aéroports de Stockholm et Cologne/Bonn sont le nombre total d'avions, le nombre d'avion dont le niveau sonore est supérieur à une limite donnée et la durée pendant laquelle un avion est perçu. Enfin, Dickson et Bolin [28] ont modifié des bruits d'avion afin d'observer l'influence de plusieurs composantes (niveau sonore global, composantes hautes et basses fréquences, composantes tonales et buzz-saw) sur la gêne sonore. Ils ont ainsi constaté que les modifications qui impactent le plus la gêne sonore sont la modification du niveau sonore global, suivie par celle du contenu spectral.

2.3 Les indices pour caractériser les facteurs acoustiques influant la gêne

Dans cette section, les indices utilisés dans la littérature pour caractériser les facteurs acoustiques influant la gêne sonore vont être recensés par facteur acoustique caractérisé.

2.3.1 L'intensité sonore

2.3.1.1 Le niveau de pression acoustique équivalent $L_{\mathbf{eq,T}}$

Le niveau de pression équivalent $L_{\mathrm{eq,T}}$, qui représente le niveau de pression sonore qu'aurait un bruit continu de même énergie acoustique totale que le bruit fluctuant étudié sur la même période T, est obtenu par intégration du niveau de pression acoustique instantanée $L(t)$:

$$L_{\mathrm{eq,T}} = 10\log_{10}\left(\frac{1}{T}\int_0^T 10^{(L(t)/10)}dt\right) \quad (dB). \tag{1.1}$$

Ce niveau peut être pondéré afin de tenir compte du filtrage opéré par l'oreille humaine. Ainsi, le niveau de pression sonore équivalent pondéré A, noté $L_{\mathrm{Aeq,T}}$, est fréquemment utilisé dans la réglementation ainsi que dans les études qui portent sur la gêne sonore due au bruit du trafic routier en laboratoire et *in situ* (*e.g.* [103, 119, 134, 137]).

2.3.1.2 Le niveau de pression sonore équivalent jour-soir-nuit $L_{\mathbf{den}}$

Cet indice, imposé par la directive européenne 2002/49/CE [70], se calcule à partir du niveau de pression sonore sur différentes périodes en appliquant une pénalité de 5 dB(A) le soir et de 10 dB(A) la nuit pour tenir compte de la gêne plus importante en soirée et de la perturbation du sommeil la nuit. La directive européenne impose la durée de chaque période (la journée dure 12 heures, le soir 4 heures et la nuit 8 heures) mais laisse à chaque État membre la liberté de fixer les plages horaires.

Le niveau de pression sonore équivalent jour-soir-nuit se calcule comme suit :

$$L_{\text{den}} = 10 \log_{10} \left[\frac{1}{24} \left(12 \times 10^{L_{\text{day}}/10} + 4 \times 10^{(L_{\text{evening}}+5)/10} + 8 \times 10^{(L_{\text{night}}+10)/10} \right) \right] \quad (dB(A)) \tag{1.2}$$

où, en France,

- L_{day} représente le $L_{\text{Aeq,T}}$ pour la période allant de 06 h à 18 h,
- L_{evening} représente le $L_{\text{Aeq,T}}$ pour la période allant de 18 h à 22 h,
- L_{night} représente le $L_{\text{Aeq,T}}$ pour la période allant de 22 h à 06 h.

Cet indice imposé par la Commission Européenne [70] pour l'établissement des cartes de bruit est fréquemment utilisé dans les études portant sur la gêne due aux bruits de transport et les bruits industriels *in situ* (*e.g.* [96, 82, 106]). De plus, cet indice est utilisé dans des relations exposition-réponse [82] qui permettent d'évaluer les pourcentages de personnes peu gênées (%LA), gênées (%A) et très gênées (%HA) par le bruit du trafic routier, par le bruit de train, par le bruit d'avion ou par le bruit industriel. Ces relations sont recommandées par l'Agence Européenne [32] pour estimer ces pourcentages. Cependant, une étude récente menée auprès de riverains français multi-exposés aux bruits de transport a montré que ces relations ne permettaient de prédire correctement que le pourcentage de personnes très gênées par le bruit du trafic routier (*cf.* [42] et Figure 1.5).

2.3.1.3 La sonie N

La sonie N est une grandeur subjective qui traduit la sensation de l'intensité perçue. Elle s'exprime en sone, la référence d'un sone ayant été définie comme la sonie d'un son pur à 1000 Hz et 40 dB, et d'une durée supérieure à 500 ms. La sonie dépend essentiellement du niveau sonore du bruit considéré, mais aussi de sa durée, de son contenu spectral et de son évolution temporelle.

Les modèles existants de calcul de la sonie reposent sur le calcul de l'excitation de la membrane basilaire par le bruit. Le domaine fréquentiel d'audition est découpé en 24 bandes critiques, dites bandes de Bark pour le modèle de Fastl et Zwicker [34]. Sur chaque bande, à partir de l'excitation de la membrane basilaire, la sonie dite spécifique est calculée. Elle est notée N' et s'exprime en $sone/Bark$.

La sonie totale se calcule enfin par intégration des sonies spécifiques sur les 24 bandes de Bark :

$$N = \int_0^{24\ Barks} N' \times dz \quad (sone) \tag{1.3}$$

Cet indice a notamment été utilisé lors des études en laboratoire de la gêne due au bruit du trafic routier (*e.g.* [58, 61, 91, 137]).

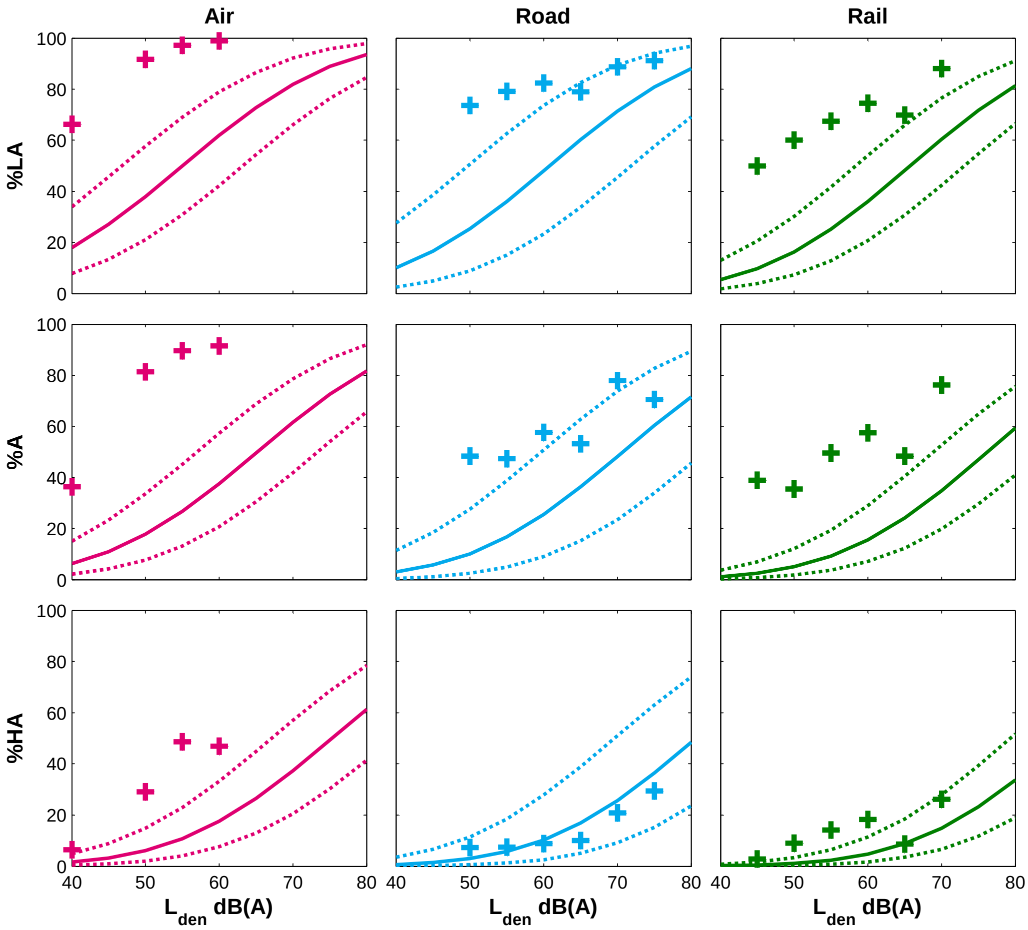

Figure 1.5 – Les relations exposition-réponse de Miedema et Oudshoorn [82] (%LA (ligne du dessus), %A (ligne du milieu) et %HA (ligne du dessous)) pour les bruits d'avion (colonne de gauche), de trafic routier (colonne du milieu) et de train (colonne de droite) en fonction du L_{den}, avec leurs intervalles de tolérance à 95%. Les pourcentages mesurés dans [42] sont représentés par des croix. Source : Figure 1 de Gille *et al.* [42]

2.3.1.4 Les indices statistiques

Un bruit variable dans le temps peut être décrit par des indices dits statistiques, notés L_X (ou N_X), qui correspondent au niveau de pression acoustique (ou à la sonie) dépassé(e) pendant X % du temps. Les principaux indices statistiques utilisés sont :

- l'indice L_1, utilisé pour estimer le niveau de bruit maximum observé,
- l'indice L_{10}, qui estime les plus hauts niveaux sonores rencontrés, même s'il peut être considérablement plus faible que le niveau crête, d'après Marquis-Favre *et al.* [78],
- l'indice L_{50} qui correspond au niveau médian,
- l'indice L_{90} qui peut être considéré comme le bruit de fond.

Ces indices ont permis de caractériser avec plus ou moins de pertinence, la gêne due au bruit de trafic routier en laboratoire (*e.g.* [58, 137]) et *in situ* (*e.g.* [67]) ainsi que la gêne due au bruit d'avion *in situ* (*e.g.* [96]).

2.3.2 Les variations irrégulières de l'amplitude

2.3.2.1 La variance de la pression pondérée A VAP

Trollé *et al.* [130] ont utilisé l'indice VAP pour rendre compte des variations irrégulières de l'amplitude : la variance de la pression pondérée A normalisée par la valeur efficace de la pression pondérée A. Cet indice se calcule comme suit :

$$VAP = \frac{V(p_A(t))}{p_A^{RMS}} \tag{1.4}$$

où V représente l'opérateur de variance, $p_A(t)$ la pression pondérée A au cours du temps et p_A^{RMS} la valeur efficace de la pression pondérée A définie comme :

$$p_A^{RMS} = \sqrt{\frac{1}{T}\int_0^T p_A(t)dt} \tag{1.5}$$

où T est la durée du stimulus.

Cet indice a été utilisé pour caractériser en laboratoire la gêne due au bruit de tramway [130, 131, 60] et celle due au bruit de passage de véhicule routier urbain [60].

2.3.2.2 L'écart-type de la pression pondérée A $STDP$

Les variations temporelles ont une influence sur la gêne due au bruit de passage de véhicules routiers urbains, mises en évidence par Morel *et al.* [91]. Pour rendre compte de ces variations, Klein [60] a proposé l'écart-type de la pression pondérée A, noté $STDP$, et défini comme suit :

$$STDP = SD(p_A(t)) \tag{1.6}$$

où SD représente l'opérateur d'écart-type et $p_A(t)$ la pression pondérée A au cours du temps.

2.3.3 Les modulations d'amplitude

2.3.3.1 La force de fluctuation F et la rugosité R

La rugosité R et la force de fluctuation F permettent de décrire la sensation engendrée par un bruit modulé en amplitude. Si la fréquence de modulation est inférieur à 20 Hz, la force de fluctuation est ressentie. Au delà, la rugosité est ressentie. Le maximum de rugosité est ressentie pour une fréquence de modulation de 70 Hz.

La force de fluctuation F, exprimée en vacil, est approximée par la relation suivante [34] :

$$F \sim \frac{\Delta L}{\frac{f_{\text{mod}}}{4} + \frac{4}{f_{\text{mod}}}}(vacil). \tag{1.7}$$

La rugosité R, exprimée en asper, est approximée par la relation suivante [34] :

$$R \sim f_{\text{mod}}\Delta L \quad (asper). \tag{1.8}$$

D'autres modèles de force de fluctuation et de rugosité existent, notamment ceux d'Aures [3] et de Daniel et Weber [4].

Ces indices ont été utilisés pour caractériser la gêne due au bruit du trafic routier *in situ* [103] et en laboratoire (*e.g.* [58, 61, 91, 137]).

2.3.3.2 Les indices "pétaradant" $m_{\mathbf{sputt}}$ et "nasal" $m_{\mathbf{nas}}$

Ces indices ont été développés par Klein *et al.* [61] pour pallier les défauts de la force de fluctuation et de la rugosité à rendre compte du caractère "pétaradant" ou "nasillard" des bruits de passage routier urbain. Ces indices se calculent sur la fenêtre temporelle i comme suit :

$$m_{sputt_i} = \left[\frac{2 \times |P_{\max}(2\ Hz - 100\ Hz)|}{P(0)}\right]_i \tag{1.9}$$

$$m_{nas,i} = \left[\frac{2 \times |P_{\max}(100\ Hz - 200\ Hz)|}{P(0)}\right]_i \tag{1.10}$$

où P est le spectre de l'enveloppe du bruit au sein de la fenêtre temporelle i avec pour composante continue $P(0)$, $|P_{\max}(2\ Hz - 100\ Hz)|$ est l'amplitude de modulation maximale dans la bande de fréquence de modulation 2 Hz - 100 Hz et $|P_{\max}(100\ Hz - 200\ Hz)|$ l'amplitude de modulation maximale dans la bande de fréquence de modulation 100 Hz - 200 Hz. Les indices statiques $m_{\mathrm{sputt},10}$ et $m_{\mathrm{nas},10}$, c'est à dire les valeurs dépassées 10% du temps, ont été utilisés pour rendre compte des sensations de modulation gênantes pour les bruits de passage de véhicules routiers urbains comprenant des deux-roues motorisés, des véhicules légers, des poids-lourds et des bus [61].

2.3.4 Le contenu spectral

2.3.4.1 L'acuité S

L'acuité S est une mesure de la densité spectrale d'un son. Elle représente l'équilibre entre les basses et les hautes fréquences et s'exprime en acum. Fastl et Zwicker [34] proposent de la calculer comme suit :

$$S = 0.11 \frac{\displaystyle\int_0^{24\ Barks} N' \times g(z) \times z \times dz}{\int_0^{24} N' \times dz} \quad (acum) \tag{1.11}$$

où z est la fréquence exprimée en $barks$ et $g(z)$ est un facteur de pondération qui est fonction des bandes critiques.

L'acuité de 1 acum correspond à l'acuité d'un bruit à bande étroite à 60 dB, de fréquence centrale 1000 Hz et de largeur de bande inférieure à 150 Hz.

Cet indice a été utilisé dans les études relatives à la gêne due au bruit de trafic routier en laboratoire (*e.g.* [39, 58, 137]) et pour caractériser la qualité sonore de bruit d'avion (*e.g.* [3]).

3. W. Aures. Ein Berechnungsverfahren der Rauhigkeit. Acustica, **66**(1), 268-281, 1985, cité dans [129].
4. P. Daniel et R. Weber. Psychoacoustical roughness : Implementation of an optimized model. Acta Acustica united with Acustica, **83**(1) : 113-123, 1997, cité dans [129]

2.3.4.2 L'énergie totale des composantes tonales $TETC_{x-y}$

L'énergie totale des composantes tonales dans les bandes critiques x à y Barks, notée $TETC_{x-y}$, a été proposée par Trollé *et al.* [130, 131] et est définie comme suit :

$$TETC_{x-y} = 10log_{10}\left(\int_x^y 10^{(L(z)/10)}dz\right) \tag{1.12}$$

où $L(z)$ représente le niveau maximal au cours du temps des composantes tonales en fonction du taux de bande critique z, calculé à l'aide du logiciel dBSonic ©.

Cet indice a été utilisé pour caractériser en laboratoire la gêne due au bruit de tramway [130, 131, 60] et celle due au bruit de trafic routier urbain [61].

2.3.5 Les indicateurs issus de combinaison d'indices

2.3.5.1 Le "Trafic Noise Index" TNI

Cet indice est calculé à partir des indices statistiques. Selon Marquis-Favre *et al.* [78], les indices statistiques sont valables pour un bruit de trafic routier où le flot de véhicules est continu et fluide. La période d'étude doit être assez longue pour considérer une représentation statistique mais pas trop pour que le bruit puisse être considéré comme stationnaire.

L'indice TNI a été introduit par Griffiths et Langdon [44] à partir d'une enquête *in situ* sur le mécontentement relatif aux conditions sonores dues au trafic routier. Il s'exprime comme suit :

$$TNI = 4(L_{10} - L_{90}) + L_{90} - 30 \tag{1.13}$$

D'après Griffiths et Langdon [44], le TNI est une tentative de description du bruit du trafic routier en combinant la plage de fluctuation du niveau sonore (*i.e.* la différence $L_{10} - L_{90}$ qui décrit le "climat sonore") et le niveau sonore absolu (représenté par le terme L_{90}).

2.3.5.2 Le niveau de pollution sonore L_{NP}

Robinson [113] propose un nouvel indice pour décrire le bruit d'avion et le bruit de trafic routier et pallier les défauts du L_{Aeq} dans la prédiction de la gêne *in situ* lors d'enquêtes.

Cet indice se calcule à partir de deux composantes : la première représente le niveau sonore équivalent continu et la seconde l'augmentation de la gêne quand des variations irrégulières d'amplitude ont lieu :

$$L_{NP} = L_{eq} + 2,56\sigma \tag{1.14}$$

avec

$$\sigma = \sqrt{\frac{1}{T}\int_0^T \left(L(t) - \frac{1}{T}\int_0^T L(t)dt\right)^2 dt} \tag{1.15}$$

où L_{eq} est le niveau de pression acoustique équivalent calculé sur la période T. La valeur $2,56$ est issue des données d'enquêtes de Robinson [113].

Robinson [113] recommande d'utiliser cet indice sur des périodes où les occurrences sonores et les activités sont à peu près homogènes.

Cet indice a été utilisé pour caractériser la gêne due au bruit d'avion (*e.g.* [110]) et l'insatisfaction (*e.g.* [67]) ou la gêne (*e.g.* [112, 139]) due au bruit de trafic routier.

2.3.5.3 Le niveau sonore équivalent corrigé L'_{eq}

Un autre indice a été proposé par Muller [94] afin de rendre compte également du niveau sonore et des fluctuations irrégulières de l'amplitude. Cet indice se calcule comme suit :

$$L'_{eq} = L_{eq} + f(\sigma') \tag{1.16}$$

avec

$$\sigma' = \sqrt{\frac{1}{T}\int_0^T \left(\frac{dL(t)}{dt}\right)^2 dt} \tag{1.17}$$

$$f(\sigma') = 10log_{10}(1 + 15\sigma') \tag{1.18}$$

Cet indice a été développé pour caractériser la gêne due au bruit d'avion [94] mais a également été utilisé pour la gêne due au bruit de trafic routier [139].

2.3.5.4 La gêne psychoacoustique PA

Cet indice a été développé par Fastl et Zwicker pour rendre compte de la gêne sonore due à des bruits de véhicules routiers. Cet indice permet de tenir compte de l'intensité sonore perçue, du contenu spectral et des modulations d'amplitude. Il se calcule comme suit :

$$PA = N_5 \left(1 + \sqrt{w_S^2 + w_{FR}^2}\right) \tag{1.19}$$

où

$$w_S = \left(\frac{S}{acum} - 1.75\right) \times 0.25 \log_{10}\left(\frac{N_5}{sone} + 10\right) \text{ pour S} > 1.75 \text{ acum} \tag{1.20}$$

$$w_{FR} = \frac{2.18}{(N_5/sone)^{0.4}}\left(0.4\frac{F}{vacil} + 0.6\frac{R}{asper}\right) \tag{1.21}$$

avec N_5 la sonie dépassée 5 % du temps, S l'acuité, R la rugosité et F la force de fluctuation.

Cet indice a également été utilisé *in situ* [103] et en laboratoire [58] pour la gêne due au bruit du trafic routier.

2.3.5.5 La gêne sonore due à des bruits de passage de véhicules routiers urbains URA

Cet indice a été proposé par Klein *et al.* [61] pour rendre compte de la gêne sonore due à des bruits de passage de véhicules routiers urbains. Cet indice URA permet de rendre compte de l'intensité sonore perçue, des modulations d'amplitude et du contenu spectral. Il se calcule comme suit :

$$URA = 0.50N_{mean} + 2.85m_{sputt,10} + 3.51m_{nas,10} + 0.026TETC_{16-24} - 0.079 \tag{1.22}$$

avec N_{mean} la sonie moyenne, $m_{sputt,10}$ et $m_{nas,10}$ les indices "pétaradant" et "nasal" dépassé pendant 10% de la durée du bruit de passage et $TETC_{16-24}$ l'énergie totale des composantes tonales dans les bandes critiques 16 à 24 Barks.

3 L'étude de la multi-exposition

Dans cette section, une définition des termes utilisés dans les études de gêne en situation de multi-exposition est donnée. Puis, les différents modèles prédictifs de la gêne en situation de multi-exposition sont décrits. Enfin, les principaux résultats issus d'enquêtes *in situ* et d'expériences en laboratoire pour les situations de multi-exposition aux bruits de trafic routier et d'avion sont présentés.

3.1 Une définition de la multi-exposition sonore

Le vocabulaire pour désigner les situations de multi-exposition est variable d'une publication à l'autre. Ainsi, certains auteurs parlent de **sources de bruit combinées** ("combined noise sources"), d'autres de **source de bruit mélangées** ("mixed noise sources"), d'autres encore de **sources de bruit simultanées** ("simultaneous noise sources") ou encore de **bruits multi-sources** ("multi-source noise").

Ainsi, d'après Champelovier *et al.* [21], une situation peut être caractérisée de situation de multi-exposition quand les individus exposés à plusieurs sources de bruit sont en capacité d'identifier les différentes sources en présence, que ce soit d'un point de vue acoustique, perceptif ou visuel. Le bruit de ces sources ne doit donc pas être assimilable à un bruit de fond.

Ces différents termes permettent de décrire les différentes situations de multi-exposition qui peuvent être rencontrées : la simultanéité des sources sonores peut être totale, partielle ou inexistante.

3.2 Définition des termes utilisés dans les études sur la multi-exposition

La gêne spécifique (ou "specific annoyance") d'une source sonore présente dans une situation de multi-exposition désigne la gêne qui serait engendrée par cette source sonore si elle était entendue seule. Ce terme diffère de celui de **gêne partielle** (ou "partial annoyance") qui désigne la gêne provoquée par une source de bruit lorsqu'elle est entendue dans une situation de multi-exposition.

La gêne totale (dénommée "total annoyance" ou "overall annoyance") désigne la gêne engendrée par la combinaison des sources sonores qui constituent la situation de multi-exposition.

3.3 Les modèles prédictifs de gêne en situation de multi-exposition

Les différents modèles prédictifs de gêne totale en situation de multi-exposition sont présentés dans cette section. Ces modèles ont pour une grande partie été répertoriés par Marquis-Favre *et al.* [77]. Les différents modèles présentés lient la gêne totale à des variables acoustiques (comme les niveaux de pression sonore, ces modèles sont dits psychophysiques) ou à des variables perceptives comme les gênes spécifiques ou partielles (ces modèles sont dits perceptifs).

Les notations suivantes seront utilisées pour la présentation des modèles :
- A_T est la gêne totale,
- A_i est la gêne spécifique de la source i,

– L_T est le niveau de pression total,
– L_i est le niveau de pression sonore de la source i de la situation de multi-exposition.

3.3.1 Le modèle de sommation énergétique

Ce modèle lie la gêne totale au niveau de bruit total :

$$A_T = aL_T + b. \tag{1.23}$$

Taylor [124] et Miedema [81] mettent en cause la validité de ce modèle, qui prédit la même gêne totale pour deux situations de multi-exposition différentes mais de même niveau sonore total.

De plus, Miedema [80] propose de tester sur les modèles de gêne totale la condition limite d'extinction de toutes les sources sauf une. Le modèle doit alors se ramener à la formulation de la gêne spécifique du bruit restant. Or, en situation de mono-exposition, ce modèle prédit les mêmes gênes spécifiques, quelques soient les sources considérées, résultat qui a été invalidé par des études *in situ* (*e.g.* [82]).

3.3.2 Le modèle de source dominante

Ce modèle considère que la gêne totale due à la situation de multi-exposition est celle de la source la plus gênante :

$$A = \max_i A_i. \tag{1.24}$$

Ce modèle, qui vérifie la condition limite de Miedema [80], prédit généralement bien la gêne totale. Ainsi, plusieurs études *in situ* (*e.g.* [16, 95, 106]) et en laboratoire (*e.g.* [10]) ont montré que ce modèle permettait une bonne prédiction de la gêne par rapport aux autres modèles testés, malgré une surestimation de la gêne totale prédite (*e.g.* [16, 10]).

Cependant, selon Miedema [81], ce modèle n'est applicable que pour les situations où les gênes spécifiques sont bien différentes.

3.3.3 Le modèle des effets indépendants

Ce modèle exprime la gêne totale en fonction du niveau de pression sonore de chaque source combinée :

$$A_T = a_1L_1 + a_2L_2 + ... + a_nL_n + b \tag{1.25}$$

D'après Taylor [124], ce modèle fait l'hypothèse que les sources en mono-exposition ont des contributions indépendantes mais s'ajoutent, sans effet d'interaction, de masquage ou d'inhibition en situation de multi-exposition. L'interprétation psychologique la plus probable est que la gêne totale résulte d'une intégration mentale des niveaux sonores des sources séparées.

Ce modèle respecte également la condition limite de Miedema [80]. Bien que Taylor [124] ait montré une bonne prédiction de la gêne totale, Vos [136] a, au contraire, montré que ce modèle prédisait très mal la gêne totale.

3.3.4 Le modèle des différences énergétiques

Ce modèle exprime la gêne totale en fonction du niveau de pression sonore total et de la différence des niveaux de pression sonore des sources :

$$A_T = aL_T + b|L_1 - L_2| + c. \tag{1.26}$$

Ce modèle proposé par Taylor [124] est une modification du modèle de sommation énergétique. La différence des deux niveaux de pression sonore a été introduite de façon à tenir compte des effets de masquage et d'inhibition d'une source sur l'autre.

Ce modèle ne respecte pas la condition limite de Miedema [80] et bien que dans l'étude de Taylor [124], ce modèle soit celui qui offre la meilleure qualité prédictive, dans d'autres études, comme celle de Morel *et al.* [93], ce modèle n'apporte pas d'amélioration en comparaison du modèle de sommation énergétique.

Enfin, ce modèle ne peut être appliquée aux situations qui comportent plus de deux sources sonores.

3.3.5 Le modèle quantitatif de Vos [136]

Ce modèle a été développé par Vos [136], en s'intéressant à la gêne totale due à un bruit impulsionnel, à un bruit de trafic routier et à un bruit de transport aérien. Dans ce modèle, la gêne dépend d'un indice de bruit global L_t (*"overall or total rating sound level")*, qui correspond à la somme énergétique des niveaux de pression sonore corrigés pour correspondre au niveau sonore d'une source de référence.

Les niveaux des sources autres que la source de référence sont en effet corrigés pour correspondre au niveau que devrait avoir la source de référence pour produire la même gêne.

Dans le cas d'une multi-exposition composée de deux sources, la gêne spécifique A_1 due à la source 1 se calcule à partir du niveau sonore L_1 de la source 1 selon l'équation :

$$A_1 = a_1 L_1 + b_1$$

La gêne spécifique $A_{\text{réf}}$ due à la source de référence se calcule à partir du niveau sonore $L_{\text{réf}}$ de la source de référence selon l'équation :

$$A_{\text{réf}} = a_{\text{réf}} L_{\text{réf}} + b_{\text{réf}}$$

La pénalité à ajouter au niveau L_1 pour se ramener au niveau de pression sonore qu'aurait la source de référence qui produirait la même gêne vaut :

$$P_1 = \frac{b_1 - b_{\text{réf}} + (a_1 - a_{\text{réf}})L_1}{a_{\text{réf}}} \tag{1.27}$$

L'indice de bruit global L_t se calcule comme :

$$L_t = k \log\left(10^{\frac{L_{\text{réf}}}{k}} + 10^{\frac{L_1+P_1}{k}}\right) \tag{1.28}$$

où k est un paramètre à ajuster et vaut 10 dans le cas de l'addition énergétique. Vos [136] a établi qu'une valeur de k égale à 15 optimisait la prédiction.

Miedema [81] a ensuite donné une base théorique à ce modèle en s'appuyant sur des modèles développés en toxicologie, l'a ainsi généralisé à de nouvelles sources et l'a nommé le modèle de gêne équivalente.

3.3.6 Le modèle de sommation vectorielle

Ce modèle a été utilisé par Berglund *et al.* [10] pour déterminer la sonie totale ou la gêne due à la combinaison de deux sources sonores.

La gêne totale se calcule alors à partir des gênes spécifiques des bruits qui composent la multi-exposition et d'un terme d'interaction, noté α_{12} :

$$A_T = \sqrt{A_1^2 + A_2^2 + 2 \times A_1 \times A_2 \cos \alpha_{12}} \tag{1.29}$$

Par itération, Berglund *et al.* [10] ont trouvé que le modèle prédisait au mieux les réponses de gêne obtenues quand le terme α_{12} vaut 90°, c'est-à-dire quand le terme d'interaction est nul, et ce malgré une légère surestimation de la gêne par le modèle.

La surestimation de la gêne par le modèle de sommation vectorielle a été également montrée par Botteldooren et Verkeyn [16] et par Morel *et al.* [93].

3.3.7 Le modèle mixte

Morel *et al.* [92] proposent un nouveau modèle de gêne totale en fonction du niveau de pression sonore de chaque source et de la valeur absolue de la différence de ces niveaux, basé sur les modèles des effets indépendants et des différences énergétiques :

$$A_T = a_1 L_1 + a_2 L_2 + b|L_1 - L_2| + c. \tag{1.30}$$

D'après Morel *et al.* [92], ce modèle repose sur l'hypothèse que les auditeurs sont capables d'identifier séparément les sources et évaluent le bruit de leur environnement. Le jugement final est le résultat de cette évaluation, intégré selon un processus de sommation mentale et corrigé pour tenir compte d'éventuelles interactions entre les bruits.

Une version perceptive de ce modèle a également été testée par Pierrette *et al.* [106, 105], dans le cas d'une étude *in situ* d'une multi-exposition au bruit de trafic routier et au bruit industriel. Le modèle s'écrit alors :

$$A_T = a_1 A_1 + a_2 A_2 + b|A_1 - A_2| + c. \tag{1.31}$$

Ce modèle s'est avéré être le modèle qui permettait la meilleure prédiction de la gêne totale *in situ* parmi ceux testés par les auteurs [106, 105].

3.3.8 Le modèle de régression linéaire

Ce modèle a été proposé par Berglund et Nilsson [13], à partir de données *in situ*. La gêne totale s'exprime alors comme une somme pondérée des gênes spécifiques :

$$A_T = \sum_i w_i A_i \tag{1.32}$$

où w_i est la pondération appliquée à la source i.

D'après Berglund et Nilsson [13], la pondération w_i peut s'expliquer par le temps d'apparition de la source, ce qui est cohérent avec les phénomènes cognitifs en jeu. Cependant, Botteldooren et Verkeyn [16] soulignent que cette explication de la pondération par la durée d'apparition du bruit n'est pas valable pour toutes les sources. Ainsi, cette explication semble fonctionner pour les bruits de transports mais pas pour le bruit industriel ou le bruit des salles de danse. Botteldooren et Verkeyn [16] montrent que ce modèle permet une moins bonne prédiction des résultats que le modèle de source dominante mais une meilleure prédiction que le modèle de sommation vectorielle. Pierrette *et al.* [106, 105] ont montré que le modèle de régression linéaire est moins bon que le modèle de source dominante et que le modèle mixte.

3.4 La multi-exposition aux bruits de trafic routier et d'avion

De nombreuses études se sont intéressées au cas de la multi-exposition aux bruits de trafic routier et d'avion, que ce soit en laboratoire ou *in situ*. En effet, compte tenu de l'organisation des villes dans les pays occidentaux, il est rare d'être exposé au bruit d'avion sans être exposé à d'autres sources de bruit, notamment le trafic routier.

Lors d'une enquête sur 9 sites choisis pour étudier la combinaison de 3 niveaux de bruit d'avion et 3 niveaux de trafic routier (trafic pulsé du fait des feux de circulation et des intersections), Bottom [17] a mis en évidence une interaction entre le bruit du trafic routier et le bruit d'avion : la gêne due au bruit aérien est plus élevée quand le trafic routier est faible. Powell [111] a retrouvé ce résultat en laboratoire quand le niveau du bruit de trafic automobile est maintenu constant au cours d'une session. Au cours d'une autre expérience, Powell [109] a également observé que, pour des combinaisons de bruit d'avion et de bruit de trafic routier fluide à vitesse élevée, la gêne totale peut être inférieure à la gêne due au bruit d'avion entendu seul.

Taylor [124] a également observé *in situ* que la gêne partielle due au bruit d'avion est supérieure à la gêne totale, qui est elle-même supérieure à la gêne partielle due au bruit de trafic routier, lorsque le niveau du bruit d'avion est supérieur ou égal à celui du trafic routier. Par contre, quand le niveau du bruit du trafic routier est supérieur à celui du bruit d'avion, la gêne totale n'est pas différente des gênes partielles. Pour Taylor [124], la gêne totale est plus influencée par le niveau du bruit de trafic routier que par celui du bruit aérien et pourrait donc être estimée à partir d'une moyenne pondérée des gênes partielles, où les poids de pondération seraient liés à la durée d'apparition des sources.

Enfin, de nombreuses études ont montré que le bruit d'avion est plus gênant que le bruit du trafic routier (*e.g.* [109, 63, 124, 82]). Dans une étude portant sur la santé d'enfants vivant près d'aéroports, Berglund *et al.* [11] supposent que ceci s'explique notamment par le caractère intrusif du bruit d'avion, alors que le bruit de trafic routier est plutôt perçu comme un bruit de fond.

4 Résumé et choix méthodologiques

Ce chapitre résume les principaux concepts et résultats en lien avec les sujets traités dans cette thèse, à savoir la **gêne sonore** due au **bruit de trafic routier urbain**, entendu seul ou en situation de **multi-exposition** avec un **bruit d'avion**.

Ainsi, la Section 1 décrit les différentes sources acoustiques à l'origine des bruits de trafic routier et d'avion. Pour le bruit du trafic routier urbain, les résultats montrent que le bruit du moteur domine et qu'une attention particulière doit être portée en Europe aux deux-roues motorisés, en augmentation dans le trafic routier urbain dans différents pays de l'Union Européenne (*e.g.* [72]). Le bruit d'avion est issu de la combinaison de nombreuses sources acoustiques dont les contenus spectraux sont très différents. La gêne due au bruit du trafic routier ou encore au bruit d'avion est ainsi influencée par plusieurs facteurs acoustiques, notamment l'intensité sonore, le contenu temporel et spectral. En vue d'améliorer les modèles de gêne due à ces bruits basés uniquement sur le niveau sonore moyen, il s'avère donc nécessaire d'en améliorer la caractérisation physique et perceptive.

En Section 2, le concept de gêne sonore est introduit, de même que les facteurs acoustiques et non-acoustiques qui peuvent l'influencer. L'influence de ces facteurs sur la gêne sonore sera donc étudiée pour les bruits de trafic routier et d'avion dans le cadre de ces travaux de thèse. Les indices utilisés dans la littérature pour mesurer les facteurs acoustiques influant la gêne sonore sont recensés. Ce recensement sera utilisé lors des étapes de caractérisation physique et perceptive des bruits de trafic routier urbain et d'avion.

La Section 3 est quant à elle dédiée à la multi-exposition sonore. Ainsi, après avoir présenté les principaux modèles psychophysiques et perceptifs de gêne totale issus de la littérature, les principaux résultats concernant les situations de multi-exposition aux bruits de trafic routier et d'avion sont présentés, notamment ceux liés à l'interaction entre ces deux sources de bruit. Ces modèles seront utilisés lors de l'étude des situations de multi-exposition aux bruits de trafic routier et d'avion en laboratoire et *in situ* dans ces travaux de thèse.

En vue d'améliorer la prédiction de la gêne due au bruit de trafic routier en situation de mono-exposition et de multi-exposition quand entendu en présence de bruit d'avion, ces travaux de thèse ont été menés en 6 étapes principales.

La première étape, présentée au Chapitre 2, consiste en **l'identification de facteurs non-acoustiques influant *in situ* la gêne de long-terme en situation de multi-exposition aux bruits de trafic routier et d'avion.** Pour cela, à partir des données d'une enquête réalisée en 2012 auprès de ménages urbains français multi-exposés à ces bruits, une modélisation en équations structurelles des réponses de gêne est réalisée, en considérant des facteurs non-acoustiques relevés dans la littérature comme influant la gêne sonore. Cette étape conduit à **introduire la sensibilité au bruit dans les modèles de gêne sonore dans la suite de ces travaux de thèse.**

La deuxième étape, présentée au Chapitre 3, consiste à **identifier les paramètres du trafic routier qui influencent la gêne sonore.** Pour cela, les enregistrements de bruit de passage de véhicules routiers urbains réalisés par Morel [87] sont combinés afin de constituer des séquences de bruit de trafic routier urbain au sein desquelles un nombre limité de paramètres varient (position, durée et durée cumulée des périodes de calme, ordre et nombre de véhicules routiers urbains). Cette étape permet **la construction maîtrisée de séquences de trafic routier urbain dans la suite de ces travaux de thèse**.

La troisième étape consiste en la **caractérisation physique et perceptive de différentes compositions de trafic routier urbain à partir d'expériences conduites en laboratoire** (*cf.* Chapitre 4 pour la source en mono-exposition et Chapitre 6, Section 2.2.1 pour la source en multi-exposition). Les résultats de la deuxième étape sont utilisés pour construire les séquences sonores. **Les facteurs acoustiques influant la gêne sonore sont identifiés** sur la base de tâches de verbalisation réalisées par les participants en fin d'expérience. **Des combinaisons d'indices appropriées pour caractériser ces facteurs acoustiques influents sont ensuite introduites dans des modèles de gêne multi-niveau**, au sein desquels la sensibilité au bruit individuelle est également introduite. La quatrième étape est similaire à la troisième étape mais porte sur la **caractérisation physique et perceptive de bruits d'avion** (*cf.* Chapitre 5 pour la source en mono-exposition et Chapitre 6, Section 2.2.2 pour la source en multi-exposition).

La cinquième étape, présentée au Chapitre 6 (Section 2.5), consiste en la **caractérisation physique et perceptive des situations de multi-exposition aux bruits de trafic routier urbain et d'avion à partir d'une expérience en laboratoire.** Les phénomènes perceptifs influant la gêne totale sont étudiés sur la base des représentations de Vos [136] et les principaux modèles de gêne totale de la littérature sont évalués. Cette étape conduit à retenir certains modèles psychophysiques et perceptifs de gêne totale.

La sixième étape, présentée au Chapitre 6 (Sections 2.4 et 2.6), consiste en la **confrontation des modèles de gêne établis en laboratoire aux données de gênes partielles et de gêne totale mesurées lors de l'enquête** présentée au Chapitre 2. Pour cela, une méthodologie d'estimation des indices acoustiques à partir des valeurs du L_{den} connues *in situ* est proposée (Chapitre 6, Section 2.3). Cette confrontation conduit à **proposer des modèles de gêne pour les gênes partielles dues aux bruits de trafic routier et d'avion et des modèles perceptifs de gêne totale.**

Chapitre 2

Données de gêne mesurées *in situ* : Étude des facteurs non-acoustiques influents de la gêne sonore en situation de multi-exposition aux bruits de trafic routier et d'avion

Les travaux de thèse présentés dans ce chapitre ont été menés en collaboration avec Kin-Che Lam de l'Université Chinoise de Hong-Kong, lors de son séjour au Laboratoire Génie Civil et Bâtiment de l'ENTPE. Cette collaboration a porté sur la modélisation en équations structurelles des données d'une enquête socio-acoustique relative à la gêne en situation de multi-exposition aux bruits de trafic routier et d'avion.

Questions scientifiques

Les questions auxquelles nous souhaitons répondre dans ce chapitre sont les suivantes :

- ♣ Quels sont les facteurs non-acoustiques qui influencent la gêne partielle due au bruit du trafic routier ?
- ♣ Quels sont les facteurs non-acoustiques qui influencent la gêne partielle due au bruit d'avion ?
- ♣ Quels sont les facteurs non-acoustiques qui influencent la gêne totale en situation de multi-exposition aux bruits de trafic routier et d'avion ?
- ♣ Les gênes partielles ont-elles une influence sur la gêne totale en situation de multi-exposition aux bruits de trafic routier et d'avion ?

Les données recueillies lors d'une enquête socio-acoustique menée auprès de riverains exposés aux bruits de trafic routier et d'avion sont utilisées pour modéliser en équations structurelles la gêne partielle due au bruit de chacune de ces deux sources de bruit ainsi que la gêne totale due à la combinaison de ces deux sources. Cette modélisation en équations structurelles permet l'identification de facteurs non-acoustiques à considérer dans la suite de ces travaux de thèse.

Introduction

La gêne sonore est influencée par des facteurs acoustiques et non-acoustiques (*cf.* [77], Chapitre 1, Section 2.2). Or, la part de variance dans les jugements individuels de gêne expliquée par le niveau sonore est limitée, de l'ordre de 30% dans certaines études où il est exprimé en termes de L_{Aeq} (*e.g.* [9]).

Afin d'améliorer les modèles prédictifs de la gêne sonore, notamment due au bruit des transports, ces deux types de facteurs doivent donc être considérés. Pour cela, de meilleures identification et caractérisation des facteurs acoustiques et non-acoustiques sont nécessaires.

Par ailleurs, des études ont montré que nombre de nos concitoyens sont soumis à des situations de multi-exposition sonore. La gêne en situation de multi-exposition sonore est difficile à caractériser et à prédire. Il résulte de cette difficulté scientifique un vide réglementaire qui peut constituer un frein à la planification locale des opérations de rattrapage de ces situations de multi-exposition.

Dans ce contexte, le Ministère de l'Écologie, du Développement Durable et de l'Énergie a financé la réalisation en 2012 d'une enquête socio-acoustique relative à la multi-exposition sonore. Les questions de cette enquête portaient à la fois sur la gêne sonore (gêne partielle et gêne totale, *cf.* Chapitre 1, Section 3.2), sur l'exposition sonore (*e.g.* les sources sonores entendues, les périodes bruyantes de la journée) et sur les facteurs non-acoustiques (*e.g.* âge, sexe, profession) [31]. L'exposition sonore de chaque répondant a également été évaluée grâce aux cartes de bruit stratégiques disponibles pour les villes étudiées.

Les données de cette enquête socio-acoustique permettent donc d'évaluer l'influence de différents facteurs sur la gêne sonore. La première Section sera donc dédiée à la présentation succincte de l'enquête et du questionnaire. La Section 2 présentera la modélisation en équations structurelles de : i) la gêne partielle due au bruit du trafic routier, ii) la gêne partielle due au bruit d'avion et iii) la gêne totale en situation de multi-exposition sonore aux bruits de trafic routier et d'avion. Les résultats de ces modélisations seront discutés en Section 3.

1 Présentation de l'enquête relative à la gêne en situation de multi-exposition sonore

En 2012, une enquête socio-acoustique a été financée par le Ministère de l'Écologie, du Développement Durable et de l'Énergie. Cette enquête avait pour objectif l'étude de la gêne en situation de multi-exposition aux bruits de transports (*i.e.* le bruit du trafic routier combiné au bruit ferroviaire, le bruit du trafic routier combiné au bruit d'avion, le bruit ferroviaire combiné au bruit d'avion, le bruit du trafic routier combiné à la fois au bruit ferroviaire et au bruit d'avion). L'enquête, conduite par Ecotière *et al.* [31], a été menée dans 8 villes françaises.

1.1 Questionnaire de l'enquête

Le questionnaire (*cf.* [31]) était composé de questions portant sur :
– le quartier, le cadre de vie, le lieu d'habitation ;

- l'environnement sonore global ;
- le bruit des différentes sources étudiées, considérées comme isolées (*i.e.* le bruit du trafic routier, le bruit ferroviaire ou le bruit d'avion, en fonction de la ville de résidence du répondant) ;
- le bruit dû à l'ensemble des sources étudiées (*i.e.* le bruit du trafic routier combiné au bruit ferroviaire, le bruit du trafic routier combiné au bruit d'avion, le bruit ferroviaire combiné au bruit d'avion, le bruit du trafic routier combiné au bruit ferroviaire et au bruit d'avion) ;
- et les facteurs non-acoustiques relatifs au répondant, tels que la sensibilité au bruit.

Les questions relatives à la gêne sonore sont conformes aux recommandations de la norme ISO 15666 [53]. Il était demandé aux répondants de donner un jugement de gêne en considérant les 12 derniers mois (*i.e.* gêne de long-terme, *cf.* Chapitre 1, Section 2.1) sur une échelle continue, allant de "0" à "10", avec 11 étiquettes numériques régulièrement espacées et 2 étiquettes verbales aux extrémités ("pas du tout" et "extrêmement"). La sensibilité au bruit a été évaluée sur une échelle continue équivalente à celle utilisée pour l'évaluation de la gêne sonore.

1.2 Exposition sonore dans les villes étudiées lors de l'enquête

L'exposition sonore de chaque répondant a été évaluée en reportant leur adresse dans les cartes de bruit stratégiques élaborées pour ces villes par les services conventionnés avec l'État [1], et ce, conformément aux exigences de la Directive Européenne 2002/49/CE [70], c'est-à-dire une carte pour chaque source de bruit. Seules les villes exposées à la fois au bruit du trafic routier et au bruit d'avion seront considérées par la suite dans ces travaux, ce qui représente 2 villes en région parisienne, Saint-Brice-sous-Forêt exposée au bruit de l'aéroport de Roissy-Charles de Gaulle et Paray-Vieille-Poste et Athis-Mons exposées au bruit de l'aéroport d'Orly. L'exposition sonore de chaque répondant est donc décrite par deux valeurs de L_{den}, une pour le bruit du trafic routier et une pour le bruit d'avion.

A Saint-Brice-sous-Forêt, exposée au bruit de l'aéroport de Roissy-Charles de Gaulle, l'exposition au bruit du trafic routier (exprimée en termes de L_{den}, *cf.* Chapitre 1, Section 2.3.1.2) est comprise entre 53,7 et 67,5 dB(A) et l'exposition au bruit d'avion est comprise entre 52 et 54 dB(A). Cinquante-neuf habitants ont participé à l'enquête. A Paray-Vieille-Poste et Athis-Mons, exposées au bruit de l'aéroport d'Orly, l'exposition au bruit du trafic routier est comprise entre 49,9 et 77,9 dB(A) et l'exposition au bruit d'avion est de 42 dB(A). Cent cinquante-trois habitants ont participé à l'enquête. Au total, les réponses de 212 répondants vont être considérées pour étudier l'influence potentielle de facteurs acoustiques et non-acoustiques sur la gêne mesurée au cours de cette enquête pour des situations de multi-exposition au bruit de trafic routier et au bruit d'avion.

1. Les cartes de bruit utilisées pour estimer l'exposition sonore des répondants représentent des valeurs continues de L_{den} et pas seulement les isophones de 5 dB(A).

2 Modélisation en équations structurelles

2.1 Présentation de la méthodologie

Dans le présent chapitre, la modélisation en équations structurelles a été utilisée afin d'étudier les liaisons entre les facteurs non-acoustiques, l'exposition sonore et la gêne sonore (gêne partielle due au bruit du trafic routier, gêne partielle due au bruit d'avion et gêne totale). La modélisation en équations structurelles suppose des relations linéaires entre les différentes variables [55]. Contrairement aux modèles de régression, la modélisation en équations structurelles permet de tenir compte des effets à la fois directs et indirects des différentes variables entre elles. Cette modélisation permet également d'introduire dans le modèle des variables non-mesurées, appelées variables latentes : ces variables sont estimées à partir d'une combinaison de variables mesurées, appelées variables manifestes [55]. Enfin, ce type de modélisation présente l'avantage de pouvoir être représenté graphiquement.

Les modélisations en équations structurelles ont été implémentées dans le module SEPATH de Statistica. Les coefficients standardisés des modélisations ont été estimés en analysant la matrice de corrélation des variables. La qualité d'ajustement du modèle a été estimée par l'indice GFI ("Goodness of fit index"). Empiriquement, le modèle est accepté si la valeur du GFI est supérieure ou égale à 0,9 (*cf.* [55]).

2.2 Hypothèses des modèles

La construction d'un modèle en équations structurelles nécessite une première étape de spécification du modèle, qui consiste à préciser les variables à introduire et les liaisons entre variables à tester. Compte tenu des données disponibles grâce à l'enquête [31], les variables introduites dans le modèles sont :

- la gêne sonore (gêne partielle due au bruit du trafic routier, gêne partielle due au bruit d'avion, gêne totale, mesurées sur une échelle continue de "0" à "10", avec 11 étiquettes numériques régulièrement espacées et 2 étiquettes verbales aux extrémités : "pas du tout" et "extrêmement") ;
- l'exposition sonore (mesurée par le L_{den} de chaque source) ;
- la sensibilité au bruit (mesurée sur une échelle continue de "0" à "10", avec 11 étiquettes numériques régulièrement espacées et 2 étiquettes verbales aux extrémités : "pas du tout" et "extrêmement" ;
- l'appréciation du logement (évaluée sur une échelle verbale à 5 points : extrêmement/beaucoup/moyennement/légèrement/pas du tout satisfait) ;
- la visibilité d'une route principale depuis le logement (Pour chaque pièce du logement, la question était : "Sur quoi donnent ces pièces ?". Un ensemble de 12 choix était proposé, dont une réponse ouverte si aucun des 11 autres choix ne correspondait. Les réponses ont été recodées pour répondre par oui ou non à la question : "Y-a-t-il une route principale visible du logement ?") ;
- la perturbation par le bruit (évaluée à partir de 6 questions : "Lorsque vous êtes ici chez vous, est-ce qu'à cause du bruit extérieur à votre logement, il vous arrive : d'interrompre votre conversation / de monter le son de la télévision / d'être perturbé pendant votre lecture / d'être perturbé lorsque vous vous reposez, vous détendez / de ne pas pouvoir utiliser votre jardin ou votre balcon / de vous réveiller ?", mesurées sur une échelle verbale à 4 points : Tout le temps/Assez sou-

vent/Occasionnellement/Jamais).

Le modèle testé est représenté sur la Figure 2.1. Les liaisons entre les différentes variables à tester ont été établies à partir de modèles en équations structurelles testés dans la littérature :

- liaison A : l'exposition sonore sur la gêne sonore (*e.g.* [125, 54, 65]) ;
- liaison B : la sensibilité au bruit sur la gêne sonore (*e.g.* [125, 54, 65, 97]) ;
- liaison C : la sensibilité au bruit sur la perturbation due au bruit (*e.g.* [54, 65, 100]) ;
- liaison D : la perturbation due au bruit sur la gêne sonore (*e.g.* [54, 65, 97]) ;
- liaison E : la sensibilité au bruit sur l'appréciation du logement (Nguyen *et al.* [97] ont observé un effet de la sensibilité sur l'appréciation du cadre de vie.) ;
- liaison G : la visibilité d'une route principale depuis le logement sur la perturbation due au bruit (ce lien avait été testé par Izumi et Yano [54], mais non conservé dans leur modèle car non-significatif) ;
- liaison H : l'appréciation du logement sur la perturbation due au bruit (Izumi et Yano [54] ont testé un effet de l'appréciation du cadre de vie sur la perturbation due au bruit, mais cet effet n'a pas été conservé dans leur modèle car non-significatif) ;
- liaison I : l'exposition sonore sur la perturbation due au bruit (*e.g.* [125, 54, 65, 100]).

A notre connaissance, la liaison F (*i.e.* la sensibilité au bruit sur la visibilité d'une route principale depuis le logement) n'a pas été évaluée dans d'autres travaux de la littérature. Ce lien a été testé en supposant que les personnes sensibles au bruit pouvaient choisir leur logement en fonction de ce critère notamment.

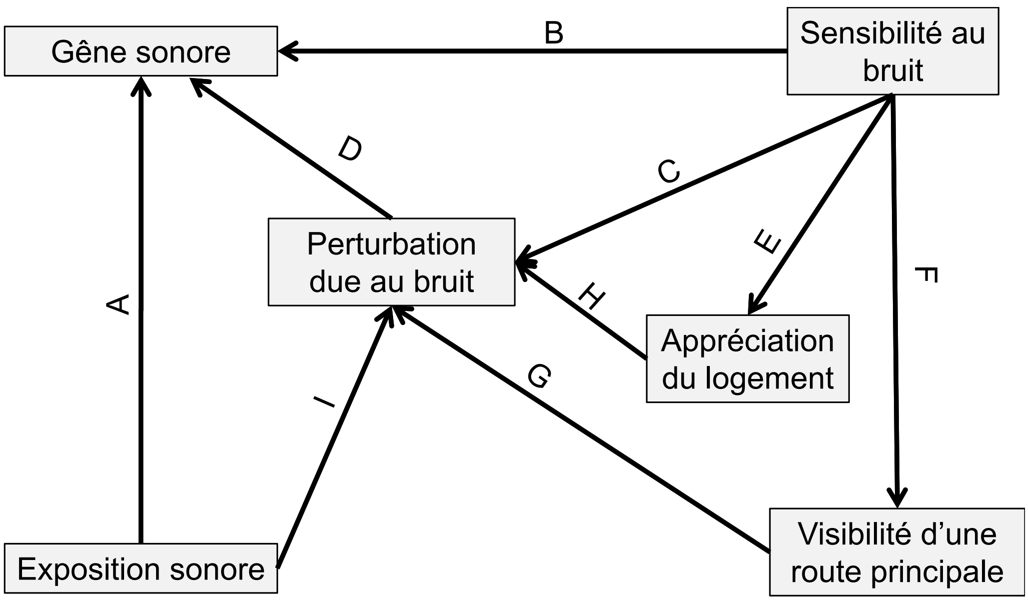

Figure 2.1 – Modèle général de la gêne sonore évalué à partir des données de l'enquête *in situ.*

2.3 Modélisation en équations structurelles des gênes partielles

Lors de l'enquête, les gênes partielles dues respectivement au bruit de trafic routier et au bruit d'avion ont été évaluées, de même que la gêne totale due à ces deux sources de bruit combinées. Les gênes partielles ont été modélisées, conformément à la Figure 2.1, en remplaçant l'exposition sonore par les valeurs du L_{den} de la source considérée et la gêne sonore par la gêne partielle correspondante. Les coefficients standardisés des modélisations en équations structurelles de la gêne partielle due au bruit du trafic routier et de la gêne partielle due au bruit d'avion sont donnés dans le Tableau 2.1, ainsi que la valeur correspondante de l'indice GFI.

Tableau 2.1 – Coefficients standardisés et indice GFI des modélisations en équations structurelles de la gêne partielle due au bruit du trafic routier et de la gêne partielle due au bruit d'avion. Tous les coefficients sont significatifs ($p<0.05$).

	Modélisation pour le bruit	
Liaison	du trafic routier	d'avion
A	0.131	0.301
B	0.315	0.260
C	0.248	0.212
D	0.372	0.249
E	-0.236	-0.236
F	0.138	0.138
G	0.218	0.257
H	-0.128	-0.138
I	0.143	0.227
GFI	0.954	0.983

Tous les coefficients sont significatifs, ce qui signifient que toutes les liaisons retenues sont pertinentes, au regard des données de l'enquête. Les liaison E et H, en lien avec l'appréciation du logement sont négatives. Ces liaisons doivent donc être interprétées comme le fait que plus les personnes sont sensibles, moins elles apprécient leur logement et donc elles sont plus susceptibles d'être perturbées par le bruit. Au contraire, toutes les autres liaisons sont positives, ce qui signifie que les variables liées évoluent dans la même direction. Ainsi, la perturbation due au bruit et la gêne sonore augmentent lorsque l'exposition sonore ou la sensibilité au bruit augmente. De même, la liaison positive F entre la sensibilité au bruit et la visibilité d'une route principale depuis le logement laisse supposer que pour un paysage urbain donné, visible à partir de la pièce, les personnes sensibles au bruit se focalisent sur la route principale.

Il apparait que les liaisons E et F obtiennent les mêmes coefficients standardisés, quelque soit la source de bruit considérée. Ceci s'explique par le fait que les variables de perturbation due au bruit, de visibilité d'une route principale et de sensibilité au bruit n'ont été relevées qu'une fois au cours de l'enquête pour cette multi-exposition, sans être déclinées pour chaque source de bruit considérée.

Les coefficients standardisés du Tableau 2.1 permettent de comparer la force des différents effets et d'obtenir les effets directs, indirects [2] et totaux (obtenus en sommant les effets direct et indirect) des variables sur la gêne sonore [22]. Ces effets sont donnés dans le Tableau 2.2.

Pour le bruit aérien, les effets totaux de l'exposition sonore et de la sensibilité au bruit

2. L'effet indirect d'une variable sur la gêne sonore est obtenu en considérant l'effet d'une variable sur la gêne sonore, par le biais d'une autre variable (*cf.* [22]). Par exemple, la sensibilité au bruit a un effet indirect sur la gêne sonore par la perturbation due au bruit, l'appréciation du logement et la visibilité d'une route principale. La valeur de l'effet indirect de la sensibilité au bruit sur la gêne sonore vaut donc $D \times (C + E \times H + F \times G)$.

Tableau 2.2 – Effets directs, indirects et totaux (*cf.* [22]) des différentes variables influant la gêne partielle due au bruit du trafic routier et la gêne partielle due au bruit d'avion.

	Modélisation pour le bruit					
	du trafic routier			d'avion		
Effet	Direct	Indirect	Total	Direct	Indirect	Total
Exposition sonore	0.131	0.053	0.184	0.301	0.057	0.358
Sensibilité au bruit	0.315	0.115	0.430	0.260	0.070	0.331
Perturbation due au bruit	0.248	-	0.248	0.212	-	0.212
Appréciation du logement	-	-0.032	-0.032	-	0.029	0.029
Visibilité d'une route principale	-	0.054	0.054	-	0.054	0.054

sur les gênes partielles sont similaires : la sensibilité au bruit contribue avec un coefficient de 0.331 au modèle et l'exposition sonore avec un coefficient de 0.358. Par contre, pour le bruit du trafic routier, la contribution de la sensibilité au bruit est bien plus importante que celle de l'exposition sonore (0.430 contre 0.184). Ces résultats confirment la nécessité de considérer la sensibilité au bruit lors de la modélisation de la gêne sonore.

2.4 Modélisation de la gêne totale due aux bruits de trafic routier et d'avion

Afin d'étudier la gêne totale en situation de multi-exposition aux deux sources de bruit, la gêne totale a été modélisée selon 2 types de modèle de la littérature (*cf.* Chapitre 1, Section 3.3) :

- modèle psychophysique : la gêne totale dépend de l'exposition sonore définie par l'indice L_{den} ;
- modèle perceptif : la gêne totale dépend des deux gênes partielles.

Ces deux modèles sont évalués dans les Sections 2.4.1 et 2.4.2, respectivement.

2.4.1 Modèle psychophysique

Un premier modèle a été testé : l'exposition au bruit de trafic routier et l'exposition au bruit d'avion influaient directement les autres variables et la satisfaction du logement n'était pas introduite. Ce modèle n'a pas été retenu car certaines liaisons étaient non-significatives, avec un indice GFI égal à 0.959. Un second modèle a été testé : l'exposition sonore pour ces situations de multi-exposition sonore a été introduite comme une variable latente, dépendante des deux variables manifestes, l'indice L_{den} de chaque source. Ce modèle, maximisant l'indice GFI (0.961) a donc été retenu, il est représenté à la Figure 2.2.

Les liaisons E et F obtiennent les mêmes coefficients standardisés que pour les gênes partielles, pour les mêmes raisons que précédemment. De plus, les expositions dues à chaque source ne contribuent pas de façon équivalente à l'exposition sonore totale : l'exposition au bruit d'avion contribue avec un coefficient de 0.714 à l'exposition sonore de ces situations de multi-exposition sonore, alors que l'exposition au bruit du trafic routier ne contribue qu'avec un coefficient de 0.330, c'est-à-dire moins de la moitié. Les effets directs, indirects et totaux des variables sur la gêne totale sont donnés dans le Tableau 2.3

La sensibilité contribue de nouveau fortement au modèle, avec un coefficient de 0.459,

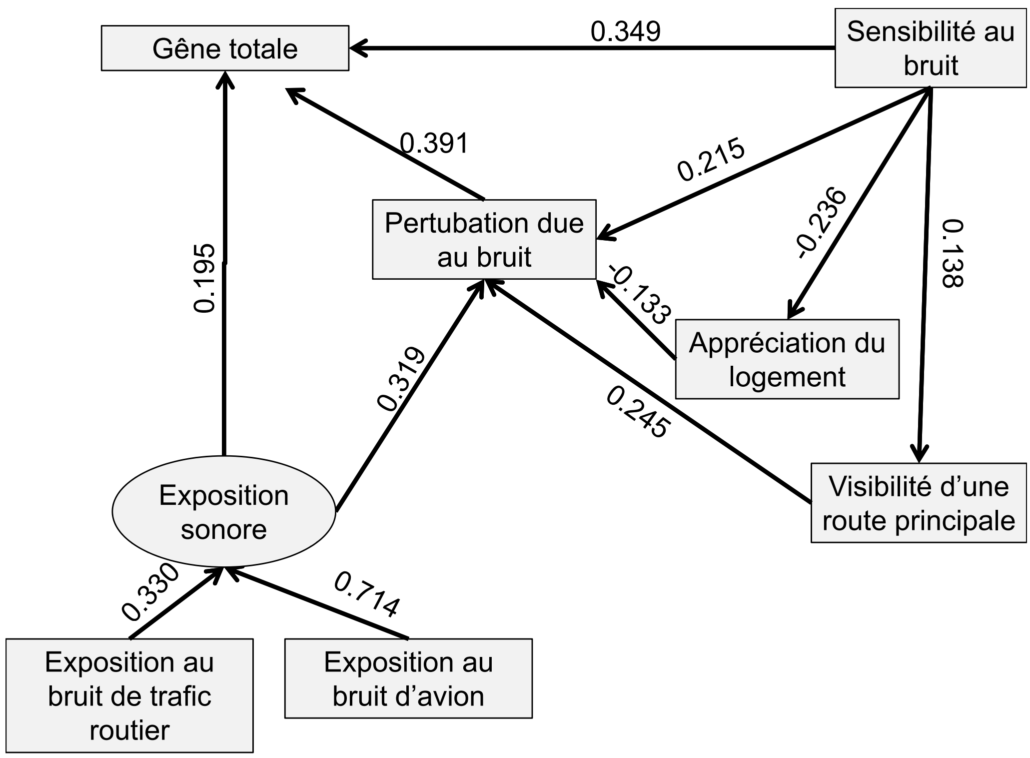

Figure 2.2 – Modèle psychophysique de la gêne totale due aux bruits d'avion et du trafic routier. GFI=0.961. Les coefficients standardisés significatifs (p≤0.05) sont donnés pour chaque liaison correspondante.

Tableau 2.3 – Effets directs, indirects et totaux (*cf.* [22]) des différentes variables influant la gêne totale selon le modèle psychophysique.

Effet	Direct	Indirect	Total
Exposition au bruit du trafic routier	–	0.106	0.106
Exposition au bruit d'avion	–	0.228	0.228
Sensibilité au bruit	0.349	0.110	0.459
Perturbation due au bruit	0.391	-	0.391
Appréciation du logement	-	-0.052	-0.052
Visibilité d'une route principale	-	0.096	0.096

suivie par l'exposition au bruit d'avion, avec un coefficient de 0.228. La contribution indirecte de l'exposition au bruit du trafic routier au modèle est moindre, de l'ordre de la moitié de celle de l'exposition au bruit d'avion. Ce résultat montre également la nécessité de considérer la sensibilité au bruit lors de la modélisation de la gêne sonore.

2.4.2 Modèle perceptif

En vue de proposer une version perceptive de la modélisation en équations structurelles de la gêne totale, les modélisations en équations structurelles de la gêne partielle due au bruit du trafic routier et de la gêne partielle due au bruit d'avion ont été combinées, ce qui a conduit au modèle perceptif, présenté à la Figure 2.3.

Une première remarque peut être formulée concernant l'absence de liaison entre l'exposition au bruit du trafic routier et la perturbation due au bruit. Cette liaison avait été introduite dans le modèle mais son coefficient standardisé non significatif a conduit à sa suppression.

Les effets directs, indirects et totaux des variables sur la gêne totale sont donnés dans le Tableau 2.4.

Alors que les gênes partielles contribuent à la gêne totale avec des coefficients standardisés similaires (0.481 pour la gêne partielle due au bruit d'avion, 0.442 pour la gêne partielle due au bruit du trafic routier), la contribution de l'exposition au bruit du trafic routier à la gêne totale est bien moindre que celle de l'exposition au bruit d'avion (0.059 contre 0.245). Ce résultat confirme le résultat établi précédemment (*cf.* Section 2.4.1), à savoir que l'exposition au bruit du trafic aérien influence plus la gêne totale que l'exposition au bruit du trafic routier. Cependant, le rapport des effets est différent (1 pour 2 dans le cadre du modèle psychophysique, 1 pour 4 dans le cas du modèle perceptif). Par contre, la contribution totale de la sensibilité au bruit par rapport à la somme des contributions des deux expositions est du même ordre de grandeur dans les deux modèles (58% pour le modèle psychophysique, 61% pour le modèle perceptif).

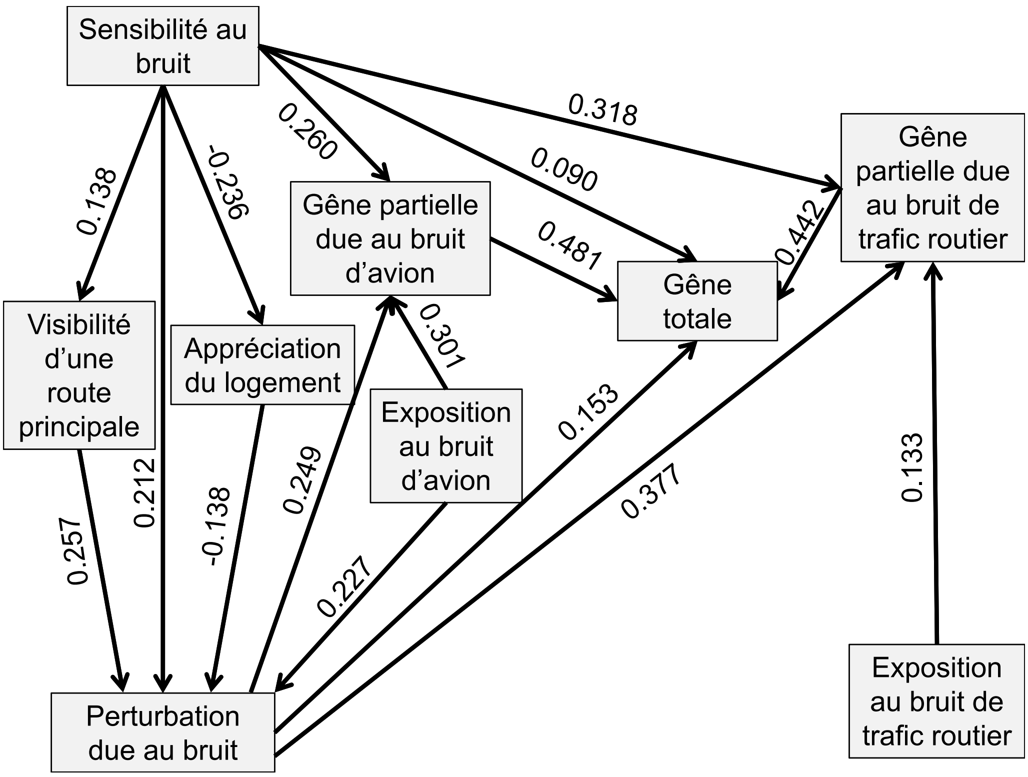

Figure 2.3 – Modèle de la gêne totale due aux bruits d'avion et du trafic routier, selon le modèle perceptif. GFI=0.919. Les coefficients standardisés significatifs ($p \leq 0.05$) sont donnés pour chaque liaison correspondante.

Tableau 2.4 – Effets directs, indirects et totaux (*cf.* [22]) des différentes variables influant la gêne totale selon le modèle perceptif.

Effet	Direct	Indirect	Total
Exposition au bruit du trafic routier	–	0.059	0.059
Exposition au bruit d'avion	–	0.245	0.245
Sensibilité au bruit	0.090	0.389	0.479
Gêne partielle due au bruit du trafic routier	0.442	-	0.442
Gêne partielle due au bruit d'avion	0.481	-	0.481
Perturbation due au bruit	0.153	-	0.153
Appréciation du logement	-	-0.021	-0.021
Visibilité d'une route principale	-	0.039	0.039

3 Discussion

Les données recueillies lors d'une enquête socio-acoustique ont été modélisées en équations structurelles afin d'évaluer les effets directs et indirects des facteurs non-acoustiques sur le jugement de gêne en situation de multi-exposition aux bruits du trafic routier et d'avion.

Les modélisations des gênes partielles ont montré que toutes les liaisons testées entre les variables sont significatives et donc pertinentes au regard des données de l'enquête. Par exemple, les facteurs non-acoustiques relatifs aux logements (*i.e.* l'appréciation du logement et la visibilité d'une route principale depuis le logement) ont un effet indirect sur la gêne sonore par la perturbation due au bruit. Un effet direct de l'appréciation du cadre de vie sur la gêne sonore a déjà été observé (*cf.* [97, 65, 54]), cependant Izumi et Yano [54] ont testé un effet de l'appréciation du cadre de vie sur la perturbation due au bruit, mais cet effet s'est avéré non-significatif. La différence entre ces résultats de la littérature et ceux établis dans cette étude peut s'expliquer par le fait que dans cette étude, le logement a été considéré, tandis que les autres études s'intéressaient au cadre de vie.

La perturbation due au bruit a quant à elle un effet direct sur la gêne sonore. Dans le cas du modèle perceptif pour la gêne totale, l'exposition au bruit du trafic routier n'influence cependant pas la perturbation due au bruit, contrairement à l'exposition au bruit d'avion. Lam *et al.* [65] ont observé un cas similaire : dans un cas de multi-exposition où le bruit du trafic routier dominait le bruit ferroviaire, la perturbation due au bruit était significativement influencée par le bruit ferroviaire, mais pas par le bruit du trafic routier. D'après Lam *et al.* [65], le bruit de trafic routier élevé, assimilable à un bruit de fond, sensibilise les répondants à une augmentation du niveau sonore due aux événements de bruit ferroviaire. Les mêmes mécanismes peuvent donc expliquer ce résultat similaire dans le cas d'une multi-exposition au bruit du trafic routier, assimilable à un bruit de fond, et au bruit d'avion, de caractère évènementiel.

Enfin, les modélisations des gênes partielles et totale ont montré que la sensibilité au bruit contribue fortement au jugement de gêne, conformément aux résultats de la littérature (*e.g.* [125, 65, 40]). Ce facteur doit donc être considéré lors de la modélisation de la gêne. De plus, la contribution de la sensibilité au bruit à la gêne partielle due au bruit d'avion est similaire à celle de l'exposition sonore (0.331 pour la sensibilité au bruit et 0.358 pour l'exposition sonore, *cf.* Figure 2.1 et Tableau 2.1). Par contre, pour la gêne due au bruit de trafic routier, la contribution de la sensibilité est bien supérieure à celle de l'exposition sonore (0.430 pour la sensibilité au bruit et 0.184 pour l'exposition sonore, *cf.* Figure 2.1 et Tableau 2.1). Cet écart entre les deux sources de bruit est peut-être dû au niveau de tolérance de la communauté. En effet, dans une étude considérant différents aéroports internationaux dont les aéroports d'Orly et de Roissy-Charles-de-Gaulle, Fidell *et al.* [35] ont montré que le niveau de tolérance de la communauté vis-à-vis de la pollution sonore est spécifique à chaque aéroport. Dans la présente étude, les réponses obtenues auprès de riverains des aéroports d'Orly et de Roissy-Charles-de-Gaulle sont agrégées, à l'image de différents travaux menés dans la littérature (*e.g.* [82]). Il peut donc y avoir un effet sur le jugement de gêne de l'aéroport auquel les riverains sont exposés (Roissy-Charles-de-Gaulle ou Orly). L'exposition sonore au bruit d'avion donnée en L_{den} rend déjà compte de l'aéroport auquel les riverains sont exposés, puisqu'il n'y a pas de recouvrement des intervalles de L_{den} entre les expositions sonores des 2 villes. Ainsi, la variable "exposition au bruit d'avion" introduite dans les modèles peut donc rendre compte aussi du facteur non-acoustique lié au lieu de résidence, et du niveau de tolérance de la communauté. En effet, les sensibilités au bruit moyennes des riverains enquêtés de chaque ville sont significativement différentes : les riverains de l'aéroport de Roissy-Charles de Gaulle sont significativement plus sensibles que les riverains d'Orly. Cela peut peut-être s'expliquer par les différences d'exposition au bruit d'avion. En effet, l'exposition au bruit d'avion diffère entre les deux villes à la fois en termes de trafics d'avions de passagers et de frets (il y a environ 2,2 fois plus de passagers et 22 fois plus de tonnes de fret à Roissy-Charles-de-Gaulle qu'à Orly), en termes de plages horaires (il y a un couvre-feu sur Orly mais pas sur Roissy-Charles de Gaulle) mais aussi en termes d'orientation des pistes par rapport à la ville (la ville étudiée près de Roissy-Charles-de-Gaulle est dans le prolongement des pistes alors que la ville étudiée près d'Orly est située parallèlement aux pistes). La variable "exposition sonore" dans la modélisation de la gêne partielle due au bruit d'avion contribue donc peut-être autant que la sensibilité au bruit car elle ne rend pas compte seulement de l'exposition sonore physique, exprimée en termes de L_{den}, mais aussi d'autres facteurs acoustiques (*e.g.* différences de trafic aérien) et non-acoustiques (*e.g.* niveau de tolérance de la communauté). Cette explication est peut-être également valable pour expliquer la différence de contribution entre l'exposition au bruit du trafic routier et l'exposition au bruit d'avion dans les modèles de gêne totale.

4 Conclusion

Les données recueillies lors d'une enquête menée auprès de riverains exposés aux bruits de trafic routier et d'avion [31] ont été utilisées pour modéliser la gêne partielle due à chacun de ces bruits ainsi que la gêne totale due à la combinaison de ces bruits. Cette modélisation en équations structurelles a permis de montrer que la gêne de long-terme dépend de nombreux facteurs non-acoustiques, comme la perturbation due au bruit, l'appréciation du logement, la visibilité d'une route principale depuis le logement et la sensibilité au bruit.

Seules l'exposition au(x) bruit(s) et la sensibilité au bruit ont été introduites comme des variables indépendantes des autres variables et leurs contributions respectives aux modèles montrent la nécessité de considérer ces deux types de variables dans les modèles de gêne, aussi bien pour les gênes partielles que pour la gêne totale. En effet, la contribution de la sensibilité au bruit à la gêne est équivalente voire supérieure à celle de l'exposition sonore.

Enfin, dans les modèles de multi-exposition, l'exposition au bruit d'avion contribue plus que l'exposition au bruit du trafic routier à la gêne totale, alors que les gênes partielles contribuent de façon similaire dans le modèle perceptif. Plusieurs raisons ont été proposées pour expliquer cet écart, telles que le caractère évènementiel du bruit d'avion comparé au bruit de trafic routier, et de plus amples investigations sont nécessaires pour infirmer ou confirmer ces propositions d'explications.

Résumé des principaux résultats obtenus

♣ La perturbation due au bruit, l'appréciation du logement, la visibilité d'une route principale depuis le logement et la sensibilité au bruit sont des facteurs non-acoustiques qui influencent la gêne partielle due au bruit du trafic routier, la gêne partielle due au bruit d'avion et la gêne totale en situation de multi-exposition aux bruits de trafic routier et d'avion.
♣ La contribution de la sensibilité au bruit à la gêne de long-terme est équivalente voire supérieure à celle de l'exposition sonore.
♣ Les gênes partielles de chaque source contribuent à la gêne totale avec des coefficients similaires dans le modèle perceptif.
♣ Dans les modèles de gêne totale en situation de multi-exposition, l'exposition au bruit d'avion contribue plus à la gêne totale que l'exposition au bruit du trafic routier.

Et après ?

Ce chapitre a montré la nécessité de considérer non seulement l'exposition sonore mais aussi la sensibilité au bruit dans les modèles de gêne. Les Chapitres 4 et 5 s'attacheront à mieux caractériser la gêne due aux bruits de trafic routier urbain et d'avion, respectivement. Plusieurs combinaisons d'indices seront ainsi proposés pour caractériser la gêne sonore, en considérant également la sensibilité au bruit.

Les données d'exposition des répondants à l'enquête présentées dans ce chapitre vont également être utilisées afin de construire les séquences sonores étudiées en laboratoire pour caractériser la gêne due au bruit d'avion et aux situations de multi-exposition aux bruits de trafic routier et d'avion (*cf.* Chapitres 5 et 6).

Avant de s'intéresser au Chapitre 4 à la caractérisation physique et perceptive du bruit de différentes compositions du trafic routier urbain en conditions contrôlées, le Chapitre 3 présente une étude sur l'effet de différentes variables acoustiques sur la gêne due au bruit du trafic routier urbain évaluée en conditions contrôlées.

Chapitre 3

Étude de l'influence sur la gêne de facteurs acoustiques relatifs aux périodes de calme, à l'ordre et au nombre de véhicules routiers urbains

Ce chapitre est composé d'un article accepté pour publication par Acta Acustica united with Acustica. Cet article est intitulé ***"Noise annoyance due to urban road traffic with powered-two-wheelers : quiet periods, order and number of vehicles"****. Il est co-écrit avec Catherine Marquis-Favre et Achim Klein, qui a réalisé les 2 expériences pilotes présentées en Sections 1 et 2. Les travaux de thèse présentés en Sections 3 à 6 reposent sur ces expériences pilotes qui sont brièvement décrites dans ce chapitre.*

Questions scientifiques

Les questions auxquelles nous souhaitons répondre dans ce chapitre sont les suivantes :

♣ La présence de périodes de calme entre les évènements sonores d'une séquence de trafic routier urbain a-t-elle une influence sur la gêne due à la séquence de trafic routier urbain ?

♣ La durée de ces périodes de calme a-t-elle une influence sur la gêne due à la séquence de trafic routier urbain ?

♣ La distribution des périodes de calme au sein de la séquence sonore a-t-elle une influence sur la gêne due à la séquence de trafic routier urbain ?

♣ La présence de périodes de calme positionnée au début ou à la fin de la séquence sonore construite a-t-elle une influence sur la gêne due à la séquence de trafic routier urbain ?

♣ Le nombre d'évènements a-t-il une influence sur la gêne due à la séquence de trafic routier urbain ?

♣ L'ordre des évènements au sein de la séquence sonore a-t-il une influence sur la gêne due à la séquence de trafic routier urbain ?

Des expériences avec mise en situation ont été réalisées, pour lesquelles les participants ont évalué la gêne due à des séquences courtes alternant des bruits de passage de véhicules (notamment des deux-roues motorisés) et des périodes de calme. Les facteurs précédemment cités sont ainsi étudiés, du point de vue de leur influence sur les jugements de gêne de court-terme (*cf.* Chapitre 1, Section 2.1). Les résultats ainsi obtenus permettront au Chapitre 4 la construction de séquences plus longues de bruit de trafic routier urbain dans l'objectif de caractériser le bruit de trafic routier urbain du point de vue de la gêne de court-terme, et ce, en maîtrisant l'influence de ces facteurs.

Abstract

This paper aims to assess the influence of different acoustical characteristics of urban road traffic including powered-two-wheelers on noise annoyance. The factors studied under laboratory conditions are the number and order of the different urban road traffic noise events, and the position and duration of quiet periods between noise events as well as their cumulative duration. Several listening experiments were carried out. The urban road traffic noise sequences were presented to a panel of participants for short-term noise annoyance assessment. First, the presence of quiet periods was found to reduce noise annoyance but there is no effect of the duration and the position of quiet periods on noise annoyance due to urban road traffic noise. For both non-equalized and equalized noise events in A-weighted equivalent sound pressure level, their order within the sequence was not found to impact noise annoyance. It seems that annoyance due to urban road traffic noise is determined by the presence of a particularly annoying noise event without consideration for its noise level. The findings of this study will contribute to the understanding of the influence of the studied acoustical factors on noise annoyance due to urban road traffic. Furthermore, the gained knowledge may be used to develop models for the assessment of noise annoyance due to urban road traffic.

Introduction

The European directive 2002/49/EC [70] requires that cities over 100,000 inhabitants produce strategic noise maps for environmental noise sources, such as industrial sites and road, rail and air traffic. The index L_{den} – the day-evening-night level [70] – is used for the construction of noise maps. As several annoyance models are based on this index [82], noise maps may be interpreted as annoyance maps. For road traffic noise maps, two main drawbacks can be mentioned. First, powered-two-wheelers (PTWs), such as motorcycles or scooters, are considered as light vehicles in the construction of the current noise maps. Whereas they are often cited among the most annoying noise source in survey (*e.g.* [38, 13]), they are little studied in literature dealing with annoyance due to urban road traffic. Furthermore, their use over the past 10 years has increased considerably (*e.g.* [72]). Concerning the second drawback of road traffic noise maps, it is well known that acoustical energy-based indices, such as the L_{den}, explain only a small part of variance in noise annoyance (*e.g.* [57]). This index takes into account the effect of only one acoustical factor – the noise level – whereas different acoustical factors are known to influence noise annoyance responses [2, 30]. Several studies (*e.g.* [58]) showed the influence of spectral and temporal features of road traffic noise on annoyance. Few studies investigated the influence of these features on annoyance due to urban road traffic noise including PTWs. For example, Vos [137] found a better correlation between noise annoyance and several psychoacoustical indices, such as fluctuation strength, roughness (*cf.* Chapter 1, Section 2.3.3.1) and loudness (*cf.* Chapter 1, Section 2.3.1.3), than between noise annoyance and A-weighted sound pressure level. Paviotti and Vogiatzis [103] identified maximum sound pressure level and roughness indices as characteristics of the noise signature of the PTWs.

Concerning road traffic noise with heavy vehicles, Björkman [15] demonstrated that an increase in the number of heavy vehicles leads to an increase in the extent of *in situ* noise annoyance. The author identified a breakpoint, after which a further increase in the number of heavy vehicles does not induce a further increase in annoyance. It will be interesting to investigate if a breakpoint can be found when the number of urban road vehicle pass-by noises with PTWs is increased. For identical numbers of vehicles, Kaczmarek and Preis [58] studied different time structures of the traffic flow. They showed that noise annoyance is well correlated with mean loudness.

Loudness is actually well known to be a basis of noise annoyance [47]. This was highlighted in studies dealing with annoyance due to road traffic noise [58, 90, 137]. Studies on loudness assessment [123, 108] have demonstrated that sounds with different time-intensity profiles lead to different loudness ratings and that the time-intensity profile has an effect on temporal weights for loudness [98]. These differences in the temporal structure might contribute to urban road traffic noise annoyance. As the different noise events of urban road traffic noise have different slopes of loudness versus time, the order of the different noise events within the urban road traffic noise sequence may have an influence on annoyance. If such effect exists, it would be of great importance to take it into account for the construction of road traffic noise sequences for laboratory studies.

To enhance noise annoyance models in future studies, it is necessary to gain understanding of the influence of the different acoustical factors (*cf.* Chapter 1, Section 2.2.2) on annoyance due to urban road traffic noise, when PTWs are considered in presence of other urban road vehicles such as buses, heavy and light vehicles.

The potential influence of different acoustical factors will be investigated by considering urban road traffic noise in cities comprising PTWs, buses, heavy and light vehicles, under laboratory conditions. First, noise annoyance due to single urban road vehicle pass-by noises is assessed in laboratory conditions. Two pilot experiments are conducted in order to gather noise annoyance ratings for each single urban road vehicle pass-by noise. In Experiment A (Exp. A), single urban pass-by noises are equalized to the same A-weighted equivalent sound pressure level (L_{Aeq}), whereas in Experiment B (Exp. B), they exhibit different L_{Aeq}. The results from both experiments will be useful to select single urban pass-by noises, considering their annoyance ratings, for the construction of urban road traffic sequences in the main Experiments I and II of this work. These main experiments aim to investigate the influence of acoustical factors on annoyance due to urban road traffic noise. In Experiment I (Exp. I), the studied factors are: the position and duration of quiet periods, their cumulative durations and the number and order of urban road traffic pass-by noises (also called noise events). All types of urban road traffic vehicles at constant speed (PTWs, buses, heavy and light vehicles) will be used and equalized in L_{Aeq}, in order to assess a potential source effect without influence of the noise level. Experiment II (Exp. II) will focus on fewer factors. First, the effect of the number of noise events within the sequence will be studied. Therefore, all types of urban road traffic vehicles (PTWs, buses, heavy and light vehicles) in different driving conditions (acceleration, deceleration and constant speed) will be included. Then, the order of noise events will be studied by considering sequences with different urban vehicles at constant speed. All the pass-by noises used in Exp. II will exhibit differences in equivalent sound pressure levels, according to *in situ* measurements.

This paper is organized as follows: the pilot experiments A and B considering single urban road vehicle pass-by noises are presented in Section 1. Section 2 presents the results of the pilot experiments. Sections 3 and 4 present the main experiments Exp. I and Exp. II, respectively, and their results. A discussion is given in Section 5.

1 Pilot experiments: noise annoyance due to single urban road traffic events [1]

Two pilot experiments Exp. A and Exp. B were carried out, considering the single urban road traffic noise events, in order to obtain the annoyance rating of each noise event. These ratings will be used in this work to select the single events for the construction of the urban road traffic sequences in Exp. I and II. This will contribute to the understanding of the potential influence of each noise event on the judgment of the annoyance due to a road traffic. [2]

1.1 Stimuli of Exp. A and B

The stimuli are single urban road vehicle noise events stemming from the perceptual typology of Morel *et al.* [90]. They were recorded in Lyon (France) and its suburbs using the ORTF technique (two cardioïd microphones spread to a 110° angle and spaced 17 cm apart) in accordance with French standards (*cf.* [90] for further details). This recording technique used for stereophonic sound reproduction in laboratory is known for its good representation, readability, plausibility and overall reproduction quality for fixed and moving noise sources [45].

The typology of Morel *et al.* [90] was composed of 57 pass-by noises and structured according to the type of urban road vehicles (PTWs, buses, heavy and light vehicles) and their driving conditions (acceleration, deceleration, constant speed), resulting in 7 perceptual and cognitive categories, (category 1: PTWs at constant speed; category 2: PTWs in acceleration; category 3: buses, heavy and light vehicles at constant speed; category 4: PTWs in deceleration ; category 5: buses, heavy and light vehicles in deceleration; category 6: light vehicles in acceleration; category 7: buses and heavy vehicles in acceleration). To limit the number of stimuli for Exp. A and B, 33 pass-by noises were selected from the perceptual categories based on the following criteria: (i) for categories consisting of 4 pass-by noises, all the pass-by noises were chosen; (ii) regarding pass-by noises from categories comprising a larger number of stimuli, a maximum of five pass-by noises per category was selected according to their note of category representation measured by Morel *et al.* [90]. The pass-by noises are denoted xyz_N as follows: x for "vehicle type" (b = bus; d = PTW; p = heavy vehicle; v = light vehicle), y for "driving condition" (a = acceleration; d =

1. Cette section résume 2 expériences menées dans les travaux de thèse d'A. Klein [60] sur lesquels reposent les travaux de thèse présentés dans ce chapitre en Section 3 à 6.

2. Furthermore, the ratings obtained from these 2 pilot experiments were used in another work (*cf.* [61]) to physically and perceptually characterize the different noise events, in order to get an annoyance model for single road events.

deceleration; f = constant speed), z for "road morphology" (o = open street; u = U-shaped street) and N an arbitrary number to differentiate stimuli.

The stimulus duration ranged from approximately 3 to 9 s. Previous studies demonstrated that the stimulus duration has a limited or no influence on short-term noise annoyance. Paulsen [101] showed that stimulus duration of highway road traffic noises ranging from 1 to 80 s had a very limited influence on annoyance judgments. For single urban road traffic pass-by noises, Morel *et al.* [91] found that stimulus duration between 3 and 9 s was not a criterion to formulate annoyance judgments. The same conclusion was drawn by Trollé *et al.* [130] for single tramway pass-by noises with durations ranging from 8 to 25.5 s.

In Exp. A, the 33 single pass-by noises were equalized to the same A-weighted equivalent sound pressure level (L_{Aeq}) of 60 dB(A). In Exp. B, the same 33 single pass-by noises were employed, with sound pressure level differences (ΔL) according to *in situ* observations. The level differences (ΔL) correspond to differences between the average A-weighted equivalent sound pressure levels measured for the light vehicles at constant speed (vfo) and the average A-weighted equivalent sound pressure levels measured for other vehicles in different driving conditions (*cf.* Table 3.1). Spectral and temporal features of the single pass-by noises were not modified by applying this ΔL.

Table 3.1: Exp. B – Level differences (ΔL) between the average sound pressure levels measured *in situ* for the light vehicles at constant speed (vfo) and the average sound pressure levels measured *in situ* for other vehicles in different driving conditions (*cf.* [87]).

Vehicle type	Driving condition	Acronym	ΔL (dB(A))
Bus	acceleration	bao	+9.1
Bus	deceleration	bdo	+4.2
Bus	constant speed	bfo	+7.5
PTW	acceleration	dao	+7.2
PTW	deceleration	ddo	+4.0
PTW	constant speed	dfo	+5.3
Heavy vehicle	acceleration	pdo	+9.1
Heavy vehicle	deceleration	pao	+4.2
Heavy vehicle	constant speed	pfo	+7.3
Light vehicle	acceleration	vao	-2.4
Light vehicle	deceleration	vdo	-4.5

The reference level for light vehicles at constant speed was set to 54 dB(A) in order to obtain a sound pressure level range acceptable for listeners. From this level, the level differences ΔL were applied to the left and right channels of each pass-by noise depending on the vehicle type and the driving condition. The resulting sound reproduction levels for the different pass-by noises of Exp. B ranged from 49 dB(A) to 62.5 dB(A), at the position of the participants in the room.

For all experiments in this paper, no filter simulating facade transmission was applied to the stimuli as wall material and window types have an effect on auditory judgments [128] and the choice of one kind of facade might have been too limiting. Thus, the worst noise exposure is considered (*e.g.* [2]) such as being in private outdoor spaces.

1.2 Apparatus

The experiments took place in a quiet room with a background noise measured at 19 dB(A). The stimuli were reproduced employing a 2.1 audio reproduction system consisting of two active loudspeakers (Dynaudio Acoustics BM5A) and one active subwoofer (Dynaudio Acoustics BM9S). This kind of sound reproduction system enables good plausibility and overall reproduction of the stimuli recorded with the ORTF technique [45].

Concerning the positioning of listener and loudspeakers, the center of the interaural axis of the listener and the loudspeakers formed an equilateral triangle. This was in accordance with the recommendations given by Bech and Zacharov [7]. The loudspeakers were placed at a height of 1.20 m from the floor, and the subwoofer was placed on the floor between the loudspeakers. The user interface was programmed using MATLAB©.

1.3 Procedure

Exp. A and B were carried out in a same test. Participants were asked to imagine themselves at home while relaxing (*e.g.* reading, watching television, discussing, gardening or doing other common relaxing activities). This procedure has been used in previous works (*cf.* [130, 91]). Prior to each experiment, the participants were trained. The stimuli were presented one by one in random order.

After each stimulus, the participants were asked: "*During your relaxing activity, you hear this noise. Does this noise annoy you?*". The participants gave the ratings on a continuous scale ranging from "0" to "10", with 11 evenly spaced numerical labels and two verbal labels at both ends ("*not at all annoying*" and "*extremely annoying*").

1.4 Participants

The test was performed by 34 participants (17 male, 17 female) aged between 20 and 54 years (mean age = 32.5; standard deviation = 11.8). All participants declared normal hearing abilities and were paid for their participation. In order to evaluate a potential effect of the experiment order (Exp. A followed by Exp. B or the reverse), the panel of participants was divided into two equal groups. One group performed Exp. A and then participated in Exp. B. The second group carried out the two experiments in reverse order. Two-factor mixed-design ANOVAs (with one within-subject factor "Stimulus" and one between-subject factor "Order") were carried out on the annoyance responses obtained in Exp. A and Exp. B, respectively. A non-significant effect of the experiment order was observed for Exp. A and Exp. B (respectively [$F(1,32) = 0.57$; $p = 0.45$] and [$F(1,32) = 2.15$; $p = 0.15$]). Hence, the annoyance responses from the 34 participants were grouped together in order to analyze the responses respectively gathered in Exp. A and Exp. B.

2 Results [3]

2.1 Experiment A: Analysis of inter-stimulus differences

A repeated measures ANOVA was carried out on the data with the factor "Stimulus". The results showed that the stimuli had a significant effect on the annoyance responses [$F(32, 1056) = 15.47$; $p < 0.001$; ϵ [4]$=0.468$]. The proportion of variance explained by the factor "Stimulus" (measured using eta-squared, denoted as η^2) was equal to 31.9 %.

Figure 3.1 illustrates the mean annoyance rating obtained for each stimulus and the corresponding standard error indicated as vertical bars.

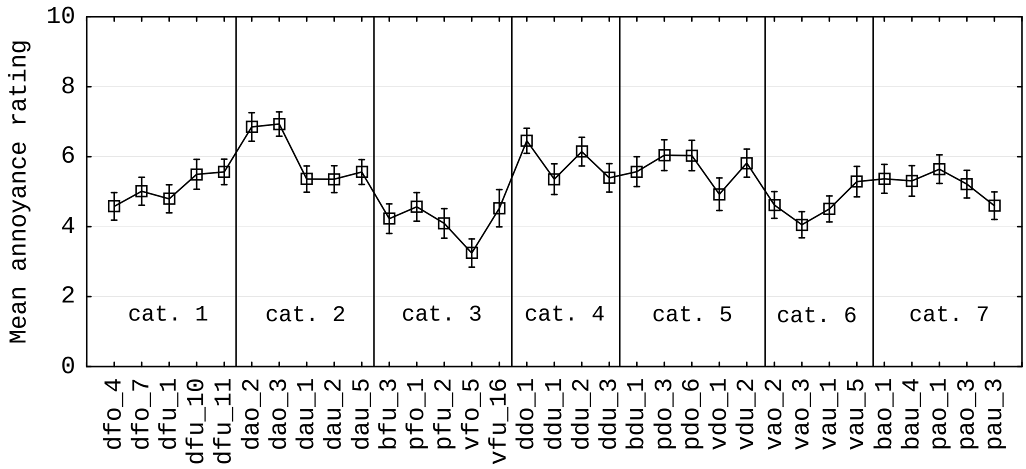

Figure 3.1: Exp. A – Mean annoyance rating for each pass-by noise equalized in A-weighted equivalent sound pressure level and the corresponding standard error (vertical bars). The perceptual categories from which the pass-by noises stem are reported (*cf.* Morel *et al.* [90]).

It can be seen that there are clear differences in mean annoyance ratings between the different urban road traffic pass-by noises equalized in L_{Aeq}. According to Tukey's HSD post-hoc test, the least annoying urban pass-by noises are a light vehicle at constant speed (vfo_5), a light vehicle in acceleration (vao_3), a bus and a heavy vehicle at constant speed (bfu_3 and pfu_2). According to the post-hoc test, the most annoying urban pass-by noises are PTWs in acceleration (dao_2, dao_3), PTWs in deceleration (ddo_1, ddu_2) and heavy vehicles in deceleration (pdo_3, pdo_6).

To study the influence of the type of vehicle [5], the driving condition and the road morphology, the annoyance ratings given by participants were averaged over pass-by noises with characteristics corresponding to the 3 studied factors (type of vehicle, driving condition and road morphology). An ANOVA was conducted considering three within-subjects factors: "Source" (denoted S, with 3 levels: d, bp or v), "Driving Condition" (denoted DC, with 3 levels: f, a or d) and "Road Morphology"(denoted RM, with 2 levels: o or u). Table 3.2 sums up the results.

This analysis showed that the 2 main factors – S and DC – and all the interactions

3. Cette section résume les principaux résultats de 2 expériences pilotes menées par A. Klein [60].
4. The Huynh-Feldt correction for the degrees of freedom (dof) [48].
5. J'ai mené cette analyse, dans le cadre de la soumission de l'article.

Table 3.2: Exp. A – Results of the ANOVA considering S (Source), DC (Driving Condition) and RM (Road Morphology) for pass-by noises equalized in A-weighted equivalent sound pressure level. SS: Sum of squares, dof: degrees of freedom, F: test statistics, p: p-value, ϵ: value of the dof Huynh-Feldt correction factor, η^2: measure of the magnitude of the experimental effect, p: p-value.

	SS	dof	F	ϵ	η^2	p
S	129.35	(2; 66)	43.45	0.94	0.12	< 0.001
DC	182.57	(2; 66)	33.88	0.72	0.16	< 0.001
RM	0.29	(1; 33)	0.25	1.00	0.00	0.62
S x DC	15.1	(4; 132)	4.19	1.00	0.01	< 0.01
S x RM	70.31	(2; 66)	33.45	0.98	0.06	< 0.001
DC x RM	21.66	(2; 66)	14.75	0.93	0.02	< 0.001
S x DC x RM	16.56	(4; 132)	4.26	0.80	0.01	< 0.01

had a significant effect on the annoyance ratings. While the S and DC factors explained respectively 12 % and 16 % of the observed variance, each interaction explained a lesser extent of the variance (between 1 % up to 6 %). On the other hand, the main factor RM did not influence annoyance ratings. This result is in agreement with the observations of Morel *et al.* [90] in a categorization task: participants noticed if the vehicle was moving in an open street or in U-shaped street, but they did not base their judgments on this factor.

As can be seen on Figures 3.2 and 3.3, the three types of vehicles are significantly different, such as the three driving conditions. This was confirmed by Tukey's HSD post-hoc tests. PTWs were judged significantly more annoying than the heavy vehicles, which were judged significantly more annoying than the light vehicles. Respectively, vehicles passing by at constant speed were judged significantly less annoying than accelerating vehicles, which were judged significantly less annoying than decelerating vehicles.

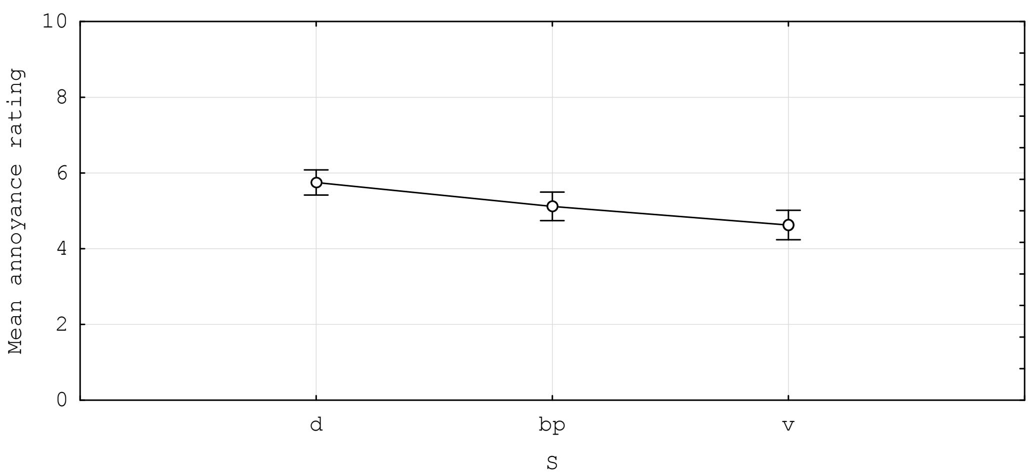

Figure 3.2: Exp. A – Exp. A – Mean annoyance rating as a function of the factor "Source" of the ANOVA and corresponding standard errors (vertical error-bars) for pass-by noises equalized in A-weighted equivalent sound pressure level. d: "PTWs"; bp: "buses and heavy vehicles"; v: "light vehicles".

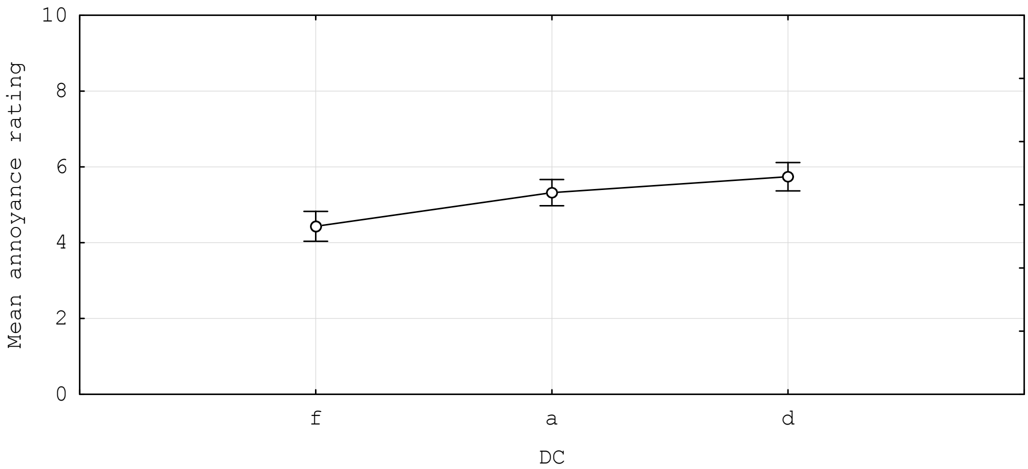

Figure 3.3: Exp. A – Mean annoyance rating as a function of the factor "Driving Condition" of the ANOVA and corresponding standard errors (vertical error-bars) for pass-by noises equalized in A-weighted equivalent sound pressure level. f: "constant speed"; a: "acceleration"; d "deceleration".

2.2 Experiment B: Analysis of inter-stimulus differences

A repeated measures ANOVA was conducted on the annoyance ratings gathered for the non-equalized 33 stimuli. Differences between annoyance ratings for the stimuli are significantly different [$F(32, 1056) = 43.056$; $p < 0.001$; ϵ=0.484]. The proportion of variance explained by the factor "Stimulus" is equal to 56 %.

In Figure 3.4, there are clearer differences between mean annoyance ratings due to the different pass-by noises compared to the mean annoyance responses obtained in Exp. A. This can be explained by the sound pressure level differences applied to the different stimuli (*cf.* Table 3.1). The light vehicles in different driving conditions are the least annoying pass-by noises and statistically differ in annoyance responses from the rest of the stimuli.

3 Experiment I: urban road traffic with single pass-by noises equalized in L_{Aeq}

For urban road traffic with different single vehicle pass-by noises (PTWs, buses, heavy and light vehicles), the influence of the following acoustical factors on noise annoyance will be investigated: the position and duration of quiet periods, their cumulative duration, the number and order of vehicle pass-by noises equalized in L_{Aeq} within the urban road traffic sequence.

For this first experiment, the different single pass-by noises (PTWs, buses, heavy and light vehicles) were equalized in L_{Aeq} in order to study the factors by limiting the effect of global loudness of each single noise event. Actually, sound stimuli equalized in sound pressure level (SPL) but with different time-intensity slopes get different global loudness evaluation [108, 107]. Furthermore, loudness appears to be an underlying basis of judged annoyance [47], confirmed by high correlation between loudness and annoyance [2, 14, 77, 87]. Thus, different slopes of loudness versus time related to different orders of the noise

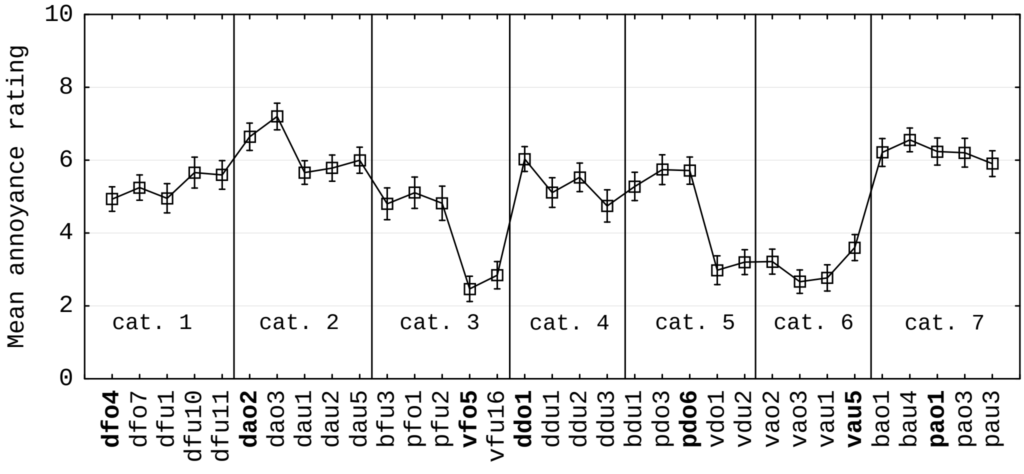

Figure 3.4: Exp. B – Mean annoyance ratings for the 33 pass-by noises non-equalized in A-weighted equivalent sound pressure level and their corresponding standard error (vertical bars). Pass-by noises rated as the most representative of their category in the experiment of Morel *et al.* [90] are reported in bold characters.

events within a sequence may impact annoyance. This effect will be studied.

Since urban road traffic with different types of vehicles is considered, the potential influence of the interaction between the investigated acoustical factors and the type of vehicle, later referred to as the "Source" factor is studied in detail.

3.1 Method

3.1.1 Stimuli

The noise sequences were composed of 2, 3 or 4 vehicle pass-by noises, separated by 0, 1 or 2 quiet period(s). During a quiet period, only the urban background noise (played for the whole duration of the noise sequence) can be heard. The urban background noise was recorded by Trollé *et al.* [130], early in the morning without distinguishable noise events in the street. The single urban road vehicle pass-by noises stemmed from Exp. A. All the noises were recorded in Lyon (France) and its neighborhood using the same procedure and apparatus (*cf.* Section 1.1). The sequences were constructed by combining different compositions of pass-by noises with different quiet period distributions.

The single urban road vehicle pass-by noises corresponded to vehicles at constant speed. Within a sequence, all the pass-by noises stemmed from the same perceptual category of Morel's typology [90] (category 1 for PTWs and category 3 for buses, heavy and light vehicles). No other driving condition (neither acceleration, nor deceleration) was considered since the short duration of the sequences does not allow to consider deceleration followed by acceleration of vehicles.

The compositions of pass-by noises studied within the different sequences were denoted as follows:

- Xd, X for "number of events" and d for "PTWs".
  - 2d: dfo_4+dfo_4;

  - 3d: dfo_4+dfo_7+dfu_1;
  - 4d: dfo_4+dfo_7+dfu_1+dfu_10.

  The selected PTWs were rated equally annoying in Exp. A (*cf.* Figure 3.1; confirmed by a Tukey's HSD test and Morel's results [91] showing no source effect within category 1 on annoyance ratings.)
- Xbp, X for "number of events" and bp for "buses and heavy vehicles".
  - 2bp: pfo_1+pfo_1;
  - 3bp: bfu_3+pfo_1+pfu_2;
  - 4bp: bfu_3+pfo_1+pfu_2+bfu_3.

  The selected pass-by noises were rated equally annoying in Exp. A from a statistical point of view (*cf.* Figure 3.1).
- Xbpv, X for "number of events" and bpv for "buses, heavy and light vehicles".
  - 2bpv: vfo_5+vfo_5;
  - 3bpv: bfu_3+vfo_5+vfo_5;
  - 3bpv_bis: vfo_5+vfo_5+bfu_3;
  - 4bpv: bfu_3+pfo_1+vfo_5+vfo_5;
  - 4bpv_bis: vfo_5+vfo_5+bfu_3+pfo_1.

  The pass-by noises composing the traffic of 3 or 4 events were rated differently in Exp. A from a statistical point of view (*cf.* Figure 3.1). Thus, the corresponding sequences (3bpv versus 3bpv_bis and 4bpv versus 4bpv_bis) were studied in two conditions: in the first condition, the more annoying noise passes by before the less annoying one (3bpv and 4bpv) and in the second condition, in reverse order (3bpv_bis and 4bpv_bis).

The 2-event sequences were constructed in the aim of studying potential effects of quiet periods (position, duration, cumulative duration) and the dependency of this effect from vehicle types (PTWs, light vehicles, buses and heavy vehicles) without considering potential order effects. For 2-event sequences, the same pass-by noise was repeated twice.

Figures 3.5 and 3.6 illustrate the loudness of the pass-by noises as a function of time, measured at the position of the participant. The loudness values were determined using dBSonic software (01dB-Metravib). Zwicker's loudness calculation is based on DIN 45631 [29].

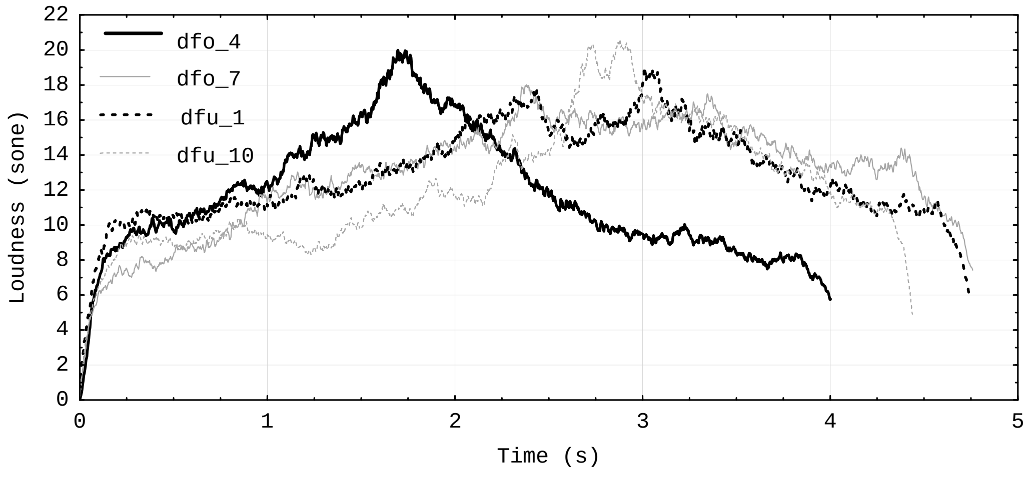

Figure 3.5: Exp. I – Loudness as a function of time for pass-by noises of category 1.

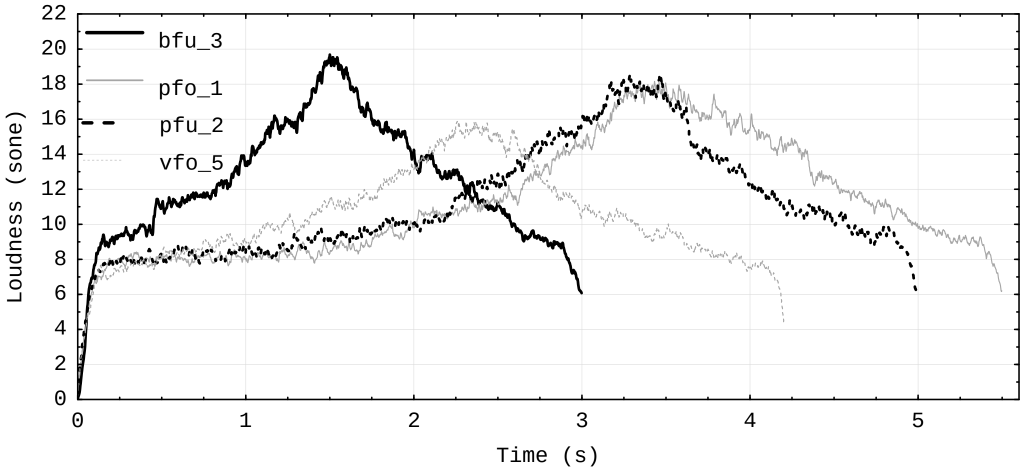

Figure 3.6: Exp. I – Loudness as a function of time for pass-by noises of category 3.

The pass-by noises were equalized to 64 dB(A) and the urban background noise to 50 dB(A). Consequently, the urban background noise was masked by the pass-by noises.

These different compositions of pass-by noises were then combined with different quiet period distributions to construct the noise sequences. A quiet period duration of 3 seconds was chosen as it corresponds to the recommendations provided by the French traffic code [71] regarding the minimal distance between vehicles to avoid collisions (at least 2 seconds). This duration is equal to the shortest pass-by noise used in this work. In addition, it corresponds to a quiet period duration of a high road traffic density. Furthermore, it is comprised in the interval of 0.5 to 5 seconds used by Kaczmarek and Preis [58] when studying road traffic noise. Table 3.3 presents the quiet period distribution (denoted as QPD in the following) used within the sequences. For each considered number of pass-by noises, the longest sequences, denoted as D1, contained 2 quiet periods between the pass-by noises. Shorter sequences (0 or 1 quiet period between the pass-by noises) were reproduced twice by extending their duration with quiet periods at the beginning or at the end, so that these sequences were of the same cumulative duration than the longest sequences. For example, the sequences D2 contained one quiet period between the noise events. These sequences were extended to be as long as the sequences D1, either with quiet periods at the end (sequences D3), or with quiet periods at the begining (sequences D4). These long sequences differed in terms of their QPDs.

Combining the different QPDs with the different compositions of pass-by noises (hereafter called "Source" and denoted S) leads to 83 sequences composed of the urban background noise and the pass-by noises (27 2-event sequences: 3 S × 9 QPDs; 28 3-event sequences: 4 S × 7 QPDs; 28 4-event sequences: 4 S × 7 QPDs). One sequence with the urban background noise alone was added to the experiment in order to test whether this background noise, which corresponds to the quiet period content of the other sequences, gets the lowest annoyance rating. Exp. I confirms this hypothesis.

Tables 3.4, 3.5 and 3.6 present the duration and L_{Aeq} [6] for each sequence.

6. L_{Aeq} is calculated over the duration of the noise sequence

Table 3.3: Exp. I – The sequences with their quiet period distribution (QPD). The letter "E" represents the pass-by noise and the letter "Q" represents a 3-second long quiet period. The quiet period distribution of each sequence is denoted Db, D for "Distribution" and b an arbitrary number to differentiate the sequences with different quiet period distributions.

Period number between events	QPD	2 events				3 events						
2 periods	D1	E	Q	Q	E	E	Q	Q	E	Q	Q	E
1 period	D2	E	Q	E		E	Q	E	Q	E		
	D3	E	Q	E	Q	E	Q	E	Q	E	Q	Q
	D4	Q	E	Q	E	Q	Q	E	Q	E	Q	E
0 period	D5	E	E			E	E	E				
	D6	E	E	Q	Q	E	E	E	Q	Q	Q	Q
	D7	Q	Q	E	E	Q	Q	Q	Q	E	E	E
	D8	Q	E	E								
	D9	Q	E	E	Q							

Period number between events	QPD	4 events									
2 periods	D1	E	Q	Q	E	Q	Q	E	Q	Q	E
1 period	D2	E	Q	E	Q	E	Q	E			
	D3	E	Q	E	Q	E	Q	E	Q	Q	Q
	D4	Q	Q	Q	E	Q	E	Q	E	Q	E
0 period	D5	E	E	E	E						
	D6	E	E	E	E	Q	Q	Q	Q	Q	Q
	D7	Q	Q	Q	Q	Q	Q	E	E	E	E

Table 3.4: Exp. I – Events equalized in A-weighted equivalent sound pressure level – Sequences with 2 events: duration and A-weighted equivalent sound pressure level[6]. QPD: Quiet Period Distribution; 2d: 2 PTW; 2bp: 2 heavy vehicles; 2bpv: 2 light vehicles.

QPD	Noise sequences					
	2d		2bp		2bpv	
	Time	L_{Aeq}	Time	L_{Aeq}	Time	L_{Aeq}
	s	dB(A)	s	dB(A)	s	dB(A)
D1	14.0	62.3	17.0	63.0	14.4	61.8
D2	11.0	63.6	14.0	63.8	11.4	62.5
D3	14.0	62.2	17.0	63.0	14.4	61.8
D4	14.0	62.2	17.0	63.0	14.4	61.8
D5	8.0	64.6	11.0	64.8	8.4	64.0
D6	14.0	62.3	17.0	63.0	14.4	61.8
D7	14.0	62.2	17.0	63.0	14.4	61.7
D8	11.0	63.3	14.0	63.8	11.4	62.7
D9	14.0	62.2	17.0	63.0	14.4	61.8

3.1.2 Apparatus, procedure and participants

The sound reproduction system consisted of the same set-up as the one used for Exp. A and B (*cf.* Section 1.2). The procedure of Exp. I is the same as the one used for Exp. A and

Table 3.5: Exp. I – Events equalized in A-weighted equivalent sound pressure level – Sequences with 3 events: duration and A-weighted equivalent sound pressure level[6]. QPD: Quiet Period Distribution; 3d: 3 PTW; 3bp: 3 buses and heavy vehicles; 3bpv and 3bpv_bis: buses, heavy and light vehicles in different orders.

QPD	Noise sequences							
	3d		3bp		3bpv		3bpv_bis	
	Time	L_{Aeq}	Time	L_{Aeq}	Time	L_{Aeq}	Time	L_{Aeq}
	s	dB(A)	s	dB(A)	s	dB(A)	s	dB(A)
D1	25.5	62.6	25.5	62.3	23.4	61.6	23.4	61.6
D2	19.5	63.7	19.5	63.4	17.4	62.8	17.4	62.8
D3	25.5	62.6	25.5	62.3	23.4	61.6	23.4	61.6
D4	25.5	62.6	25.5	62.3	23.4	61.6	23.4	61.6
D5	13.5	65.3	13.5	65.0	11.4	65.0	11.4	64.5
D6	25.5	62.6	25.5	62.4	23.4	61.6	23.4	61.6
D7	25.5	62.6	25.5	62.3	23.4	61.6	23.4	61.5

Table 3.6: Exp. I – Events equalized in A-weighted equivalent sound pressure level – Sequences with 4 events: duration and A-weighted equivalent sound pressure level[6]. QPD: Quiet Period Distribution; 4d: 4 PTW; 4bp: 4 buses and heavy vehicles; 4bpv and 4bpv_bis: buses, heavy and light vehicles in different orders.

QPD	Noise sequences							
	4d		4bp		4bpv		4bpv_bis	
	Time	L_{Aeq}	Time	L_{Aeq}	Time	L_{Aeq}	Time	L_{Aeq}
	s	dB(A)	s	dB(A)	s	dB(A)	s	dB(A)
D1	36.0	62.4	34.5	62.1	34.9	61.7	34.9	61.6
D2	27.0	63.6	25.5	63.3	25.9	62.9	25.9	62.9
D3	36.0	62.4	34.5	62.1	34.9	61.7	34.9	61.6
D4	36.0	62.3	34.5	62.1	34.9	61.7	34.9	61.7
D5	18.0	65.3	16.5	65.1	16.5	64.6	16.9	64.6
D6	36.0	62.4	34.5	62.1	34.9	61.7	34.9	61.7
D7	36.0	62.4	34.5	62.1	34.9	61.7	34.9	61.7

B (*cf.* Section 1.3, the questionnaire is similar to the one given in Appendix A, Section 1, with only questions relative to urban road traffic noise.). Exp. I lasted approximately one hour.

Thirty participants took part in Exp. I, 16 women and 14 men (mean age = 28; standard deviation = 11). All the participants declared normal hearing abilities. They were paid for their participation.

3.2 Results of the Exp. I

In the following, the annoyance ratings obtained in Exp. A for single vehicle pass-by noises will be called specific annoyance ratings, whereas the annoyance ratings obtained in Exp. I for the road traffic noise sequences will be called total annoyance ratings. First, an ANOVA was conducted considering three within-subjects factors: "Number of Events" (denoted NE, with 3 levels: 2, 3 or 4 events), "Quiet Period Distribution" (denoted QPD, with 7 levels: D1 to D7) and "Source" (denoted S, with 3 levels: d, bp or bpv). The latter factor was introduced in the ANOVA in order to investigate the interaction between the type of noise source and the other factors. Table 3.7 sums up the results.

Table 3.7: Exp. I – Events equalized in A-weighted equivalent sound pressure level – Results of the ANOVA considering NE, QPD and S. SS: Sum of squares, dof: degrees of freedom, F: test statistics, p: p-value, ϵ: value of the dof Huynh-Feldt correction factor, η^2: measure of the magnitude of the experimental effect, p: p-value.

	SS	dof	F	ϵ	η^2	p
S	851.43	(2; 58)	31.85	0.61	0.20	<0.001
NE	400.59	(2; 58)	94.03	0.77	0.09	<0.001
QPD	95.58	(6; 174)	10.11	0.81	0.02	<0.001
S x NE	19.33	(4; 116)	3.39	0.97	<0.01	0.01
S x QPD	17.18	(12; 348)	1.29	0.75	<0.01	0.22
NE x QPD	13.55	(12; 348)	1.10	0.84	<0.01	0.36
S x NE x QPD	60.80	(24; 696)	2.28	0.55	0.01	<0.001

This analysis showed that the 3 main factors – S, NE and QPD – and the S x NE and S x NE x QPD interactions had a significant effect on the annoyance ratings due to the road traffic sequences. While the S and NE factors explained respectively 20 % and 9 % of the observed variance, the QPD factor and the S x NE and S x NE x QPD interactions explained together 4 % of the variance.

3.2.1 Influence of the source

The post-hoc test performed on the S factor showed small but significant differences between the vehicle types. Figure 3.7 shows that the sequences with PTWs were judged more annoying than the ones with buses and heavy vehicles. The latter were judged more annoying than the sequences with buses, heavy and light vehicles. This result was in agreement with the trend observed in Exp. A (*cf.* Section 2.1): PTWs were among the most annoying pass-by noises whereas light vehicles were among the least annoying ones. It seems that the specific annoyance due to each single urban road vehicle influenced the total annoyance due to the sequences comprising this vehicle.

3.2.2 Influence of the number of events

The post-hoc test performed on the NE factor showed that annoyance increased with this factor, with significant differences between each number of events (*cf.* Figure 3.8).

3.2.3 Influence of the distribution of the quiet periods

The post-hoc test performed on the QPD factor showed that the sequences without quiet periods, *i.e.* D5, were significantly more annoying than the other sequences (*cf.* Figure 3.9). The other QPDs were not significantly different. Considering the non-significant

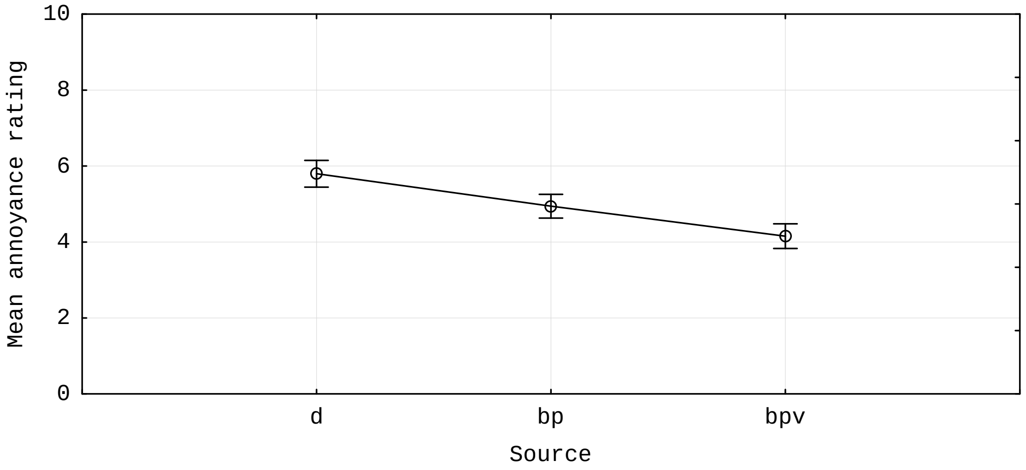

Figure 3.7: Exp. I – Events equalized in A-weighted equivalent sound pressure level – Mean annoyance rating as a function of the factor "Source" of the ANOVA and corresponding standard errors (vertical error-bars). d: "PTWs"; bp: "buses and heavy vehicles"; bpv: "buses, heavy and light vehicles".

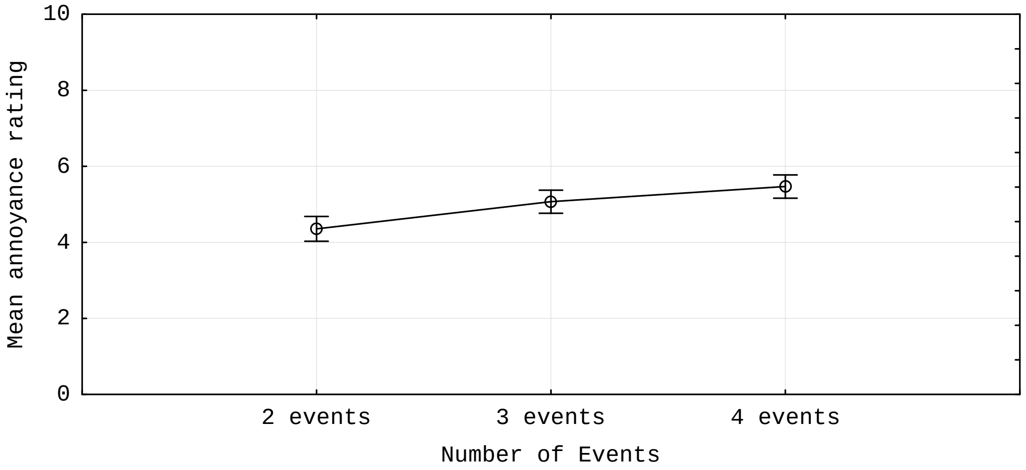

Figure 3.8: Exp. I – Events equalized in A-weighted equivalent sound pressure level – Mean annoyance rating as a function of the factor "Number of Events" of the ANOVA and corresponding standard errors (vertical error-bars).

NE x QPD interaction and the results of the post-hoc test performed on the QPD factor, the sequences having the same cumulative quiet period duration (D1, D3, D4, D6 and D7 for a given NE) were not significantly different. Therefore, the position of the quiet periods within the sequence did not have any effect on annoyance ratings. Among these studied sequences, the sequences D1 and D2 for a given NE only differed in terms of the duration of quiet periods between events (6 s compared to 3 s, respectively). Thus, the results of this experiment also demonstrated that the duration of quiet periods between the noise events did not have any effect on annoyance ratings.

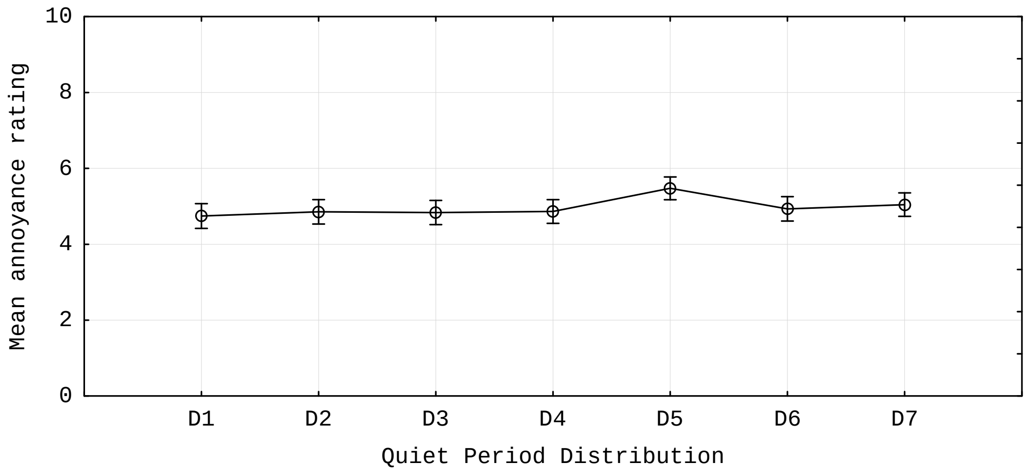

Figure 3.9: Exp. I – Events equalized in A-weighted equivalent sound pressure level – Mean annoyance rating as a function of the factor "Quiet Period Distribution" of the ANOVA and corresponding standard errors (vertical error-bars). The sequences are denoted DX, with X=1,...,7 as defined in Table 3.3.

3.2.4 Influence of the order of the noise events

To study the influence of the order of the noise events, an ANOVA was performed on the sequences bpv and bpv_bis (sequences with the same pass-bys from category 3 but presented in different orders). Three within-subjects factors are considered: NE (2 levels: 3 or 4 events), QPD (7 levels: D1 to D7) and "Position of the Most Annoying noise event" (denoted PMA, with 2 levels: beginning – for the sequences bpv – or end – for the sequences bpv_bis). Table 3.8 sums up the results.

This analysis showed that the 3 main factors – PMA, NE and QPD – had a significant effect on the annoyance ratings due to the road traffic sequences. While the QPD factors explained 10 % of the observed variance, the PMA (*cf.* Figure 3.10) and NE factor explained respectively 1 % and 2 % of the observed variance. Using Tukey's HSD post-hoc tests to compare the sequences with the same NE and QPDs but different PMA, it appears that the sequences with the most annoying noise event at the beginning were not significantly different from the sequences with this most annoying noise event at the end. The results of the post-hoc tests are the ones to consider (*cf.* [48]). Overall tests and multiple-comparison tests are different in hypotheses and in levels of power.

Table 3.8: Exp. I – Events equalized in A-weighted equivalent sound pressure level – Results of the ANOVA considering NE, QPD and PMA. SS: Sum of squares, dof: degrees of freedom, F: test statistics, p: p-value, ϵ: value of the dof Huynh-Feldt correction factor, η^2: measure of the magnitude of the experimental effect, p: p-value.

	SS	dof	F	ϵ	η^2	p
PMA	12.52	(1; 29)	7.79	1.00	0.01	<0.01
NE	19.68	(1; 29)	17.55	1.00	0.02	<0.001
QPD	120.42	(6; 174)	10.11	0.73	0.10	<0.001
PMA x NE	0.01	(1; 29)	0.01	1.00	<0.01	0.92
PMA x QPD	10.40	(6; 174)	1.66	0.72	<0.01	0.13
NE x QPD	6.15	(6; 174)	0.87	0.89	<0.01	0.52
PMA x NE x QPD	4.98	(6; 174)	0.87	0.73	<0.01	0.52

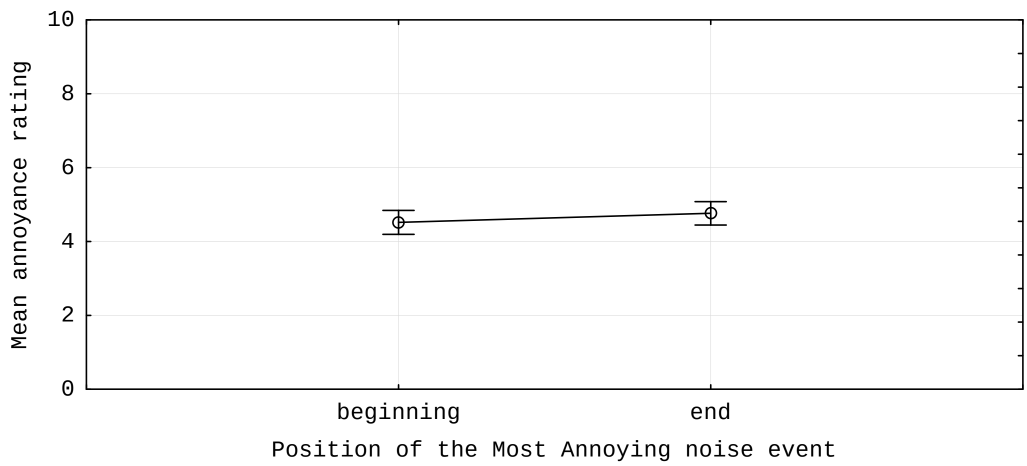

Figure 3.10: Exp. I – Events equalized in A-weighted equivalent sound pressure level – Mean annoyance rating as a function of the factor "Position of the Most Annoying noise event" of the ANOVA and corresponding standard errors (vertical error-bars).

4 Experiment II: urban road traffic with single pass-by noises at different L_{Aeq}

Exp. II was designed to test whether the results of Exp. I regarding the number and order of the pass-by noises were identical when considering vehicle pass-by noises with different L_{Aeq} and stemming from different perceptual categories of the typology [90].

4.1 Method

4.1.1 Stimuli

The urban background noise was the same as in Exp. I (*cf.* Section 3.1.1). The single vehicle pass-by noises studied in Exp. B were used in this experiment (*cf.* Section 1.1). In Exp. II, the reference noise, a light vehicle at constant speed, was equalized to 58 dB(A).

The urban background noise was equalized to 40 dB(A), in order to be masked by the pass-by noises with the lowest L_{Aeq}. The level differences observed *in situ* between the different types of vehicles at different driving conditions were applied to the pass-by noises as described in Table 3.1 (*cf.* Section 1.1).

Exp. II was composed of 17 sequences. The urban background noise was played for the whole duration of the different noise sequences. Five of these sequences were 3 minutes in duration with an increasing number of pass-by noises, from 10 to 50 with a step of 10 (*cf.* Table 3.9). Such durations of sequences allow to study different vehicles at different driving conditions (acceleration, deceleration, constant speed). For these sequences, the vehicles were chosen from the different perceptual categories of the typology [90] (*cf.* Figure 3.4). They were selected randomly within each category. The sequences reproduced typical road traffic compositions observed in Paris on the Boulevard Montparnasse, with 70 % light vehicles, 20 % PTWs and 10 % heavy vehicles [75]. Four sequences were constructed without overlap between pass-by noises and one sequence (50 vehicles) was created with overlaps between pass-by noises. The overlaps' duration was comprised between 204 ms and 4.496 s, due to the fact that certain pass-by noises ended after the next one started. With these overlaps, the identification of each pass-by noise is still possible. Table 3.9 gives the L_{Aeq} for these 5 sequences.

Table 3.9: Exp. II – Events non-equalized in A-weighted equivalent sound pressure level – A-weighted equivalent sound pressure level over the 3 minutes of the sequences

Sequence	L_{Aeq} dB(A)
10 vehicles	55.4
20 vehicles	58.6
30 vehicles	60.3
40 vehicles	61.3
50 vehicles	62.5

Twelve sequences were composed of 3 pass-by noises at constant speed: (i) one PTW, one heavy vehicle and one light vehicle, or (ii) two light vehicles and one PTW, or (iii) two light vehicles and one heavy vehicle, or (iv) two PTWs and one heavy vehicle. According to Morel *et al.* [90], the pass-by noise at constant speed chosen from the 1st or the 3rd perceptual category was rated as the most representative of its category. This is reported in bold characters in Figure 3.4: dfo_4 for category 1 and vfo_5 for category 3. In order to consider a heavy vehicle at constant speed, the pass-by noise pfo_1 was used as all heavy vehicles within the 3rd category were rated equally annoying (*cf.* Figure 3.4, and also confirmed by a post-hoc test). These sequences were also constructed in a reverse order, to study the influence of the order of pass-by noises within the urban road traffic noise on annoyance. Table 3.10 presents the 12 different sequences, their duration and their L_{Aeq} [7].

7. L_{Aeq} is calculated over the duration of the noise sequence.

Table 3.10: Exp. II – Events non-equalized in A-weighted equivalent sound pressure level – Duration and A-weighted equivalent sound pressure level L_{Aeq} [7] of the sequences with different orders of pass-by noises. In the first block, all of the 6 possible orders of the 3 different noise events are presented. In the remaining blocks, the sequences with different orders of their 2 different noise events are presented.

Sequence	Time s	L_{Aeq} dB(A)
dfo_4+pfo_1+vfo_5	13.7	64.1
dfo_4+vfo_5+pfo_1		
pfo_1+dfo_4+vfo_5		
pfo_1+vfo_5+dfo_4		
vfo_5+dfo_4+pfo_1		
vfo_5+pfo_1+dfo_4		
dfo_4+vfo_5+vfo_5	12.4	60.9
vfo_5+vfo_5+dfo_4		
pfo_1+vfo_5+vfo_5	13.9	63.0
vfo_5+vfo_5+pfo_1		
dfo_4+dfo_4+pfo_1	13.5	64.9
pfo_1+dfo_4+dfo_4		

4.1.2 Apparatus, procedure and participants

The sound reproduction system and the procedure are the same as the ones used for the previous experiments and described in Sections 1.2 and 1.3 [8]. At the end of Exp. II, the participants carried out a verbalization task [9], to identify the main acoustical features the participants noticed. They were asked to describe the road traffic sequences they heard. Exp. II lasted approximately thirty minutes.

Thirty three participants took part in Exp. II, 14 women and 19 men (mean age = 32 years; standard deviation = 12.5). All the participants declared normal hearing abilities. They were paid for their participation.

4.2 Results of the Exp. II

4.2.1 Influence of the number of events

Regarding the 3-minute sequences, the results of a repeated measures ANOVA showed a significant effect of the factor "Number of Events" on annoyance [$F(4,128) = 49.19$; $p<0.001$]. This factor explained 60 % of the observed variance. This result was expected since increasing the number of events implies an increase of the equivalent noise level of the sequences. This is also in accordance with the description of the participants: *"The road circulation is for me hardly supportable. There is the traffic density, but also the vehicle diversity."* (*"La circulation routière m'est plus difficilement supportable. Il y a la densité*

8. This experiment and the experiment presented in Chapter 5 were carried out in a same test. The study of the potential effect of the order of the experiments is presented in Appendix A, Section 2.
9. The questionnaire is common to the one given in Appendix A, Section 1, with questions relative to urban road traffic noise.

de trafic, mais aussi la diversité des véhicules.”). Figure 3.11 shows that the increase in annoyance with the number of pass-by noises was greater between 10 and 30 vehicles than between 30 and 50 vehicles. This change in annoyance variation constituted a breakpoint. It can be noticed that the breakpoint observed for 30 vehicles did not correspond to the number of events with overlaps between vehicles.

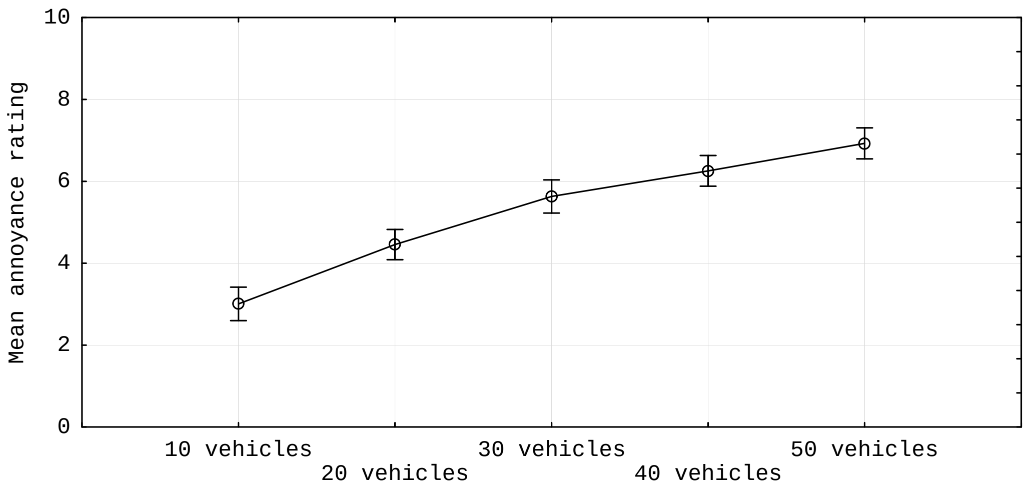

Figure 3.11: Exp. II – Events non-equalized in A-weighted equivalent sound pressure level – Mean annoyance rating as a function of the number of vehicles during 3-minute sequences and their standard errors (vertical error-bars).

4.2.2 Influence of the order of the noise events

Four repeated measure ANOVAs were performed on the sequences with 3 pass-by noises presented in different orders, one per block of the Table 3.10, to avoid the potential influence of the composition of the sequence (different types of vehicle within the sequences and, for example, different numbers of light vehicles (0, 1 or 2) within the sequences). First, an ANOVA was performed on the first block of Table 3.10 with one within-subject factor: “Order of the noise events” (6 levels). No effect of the order of the noise events was observed [$F(5,160)=0.05$; $p=0.99$; $\epsilon=0.85$]. Then, three ANOVAs were performed, one per remaining block, with one within-subject factor: “Order of the noise events” (2 levels: loudest event at the beginning or at the end). For the three ANOVAs, no effect of the order of the noise events was observed (for dfo_4+vfo_5+vfo_5 and vfo_5+vfo_5+dfo_4: $F(1,32)=2.14$; $p=0.15$; for pfo_1+vfo_5+vfo_5 and vfo_5+vfo_5+pfo_1: $F(1,32)=3.77$; $p=0.06$; for dfo_4+dfo_4+pfo_1 and pfo_1+dfo_4+dfo_4: $F(1,32)=3.62$; $p=0.07$). From Figure 3.12, it is apparent that sequences with the same pass-by noises presented in different orders were not significantly different. This result is in agreement with the tendency observed in Exp. I (*cf.* Section 3.2). Such a result was obtained in Exp. I in which the pass-bys of a noise sequence stemmed from the same perceptual categories of Morel’s typology [90] and were presented at the same L_{Aeq}. Exp II confirms this result by considering more differences between the used pass-by noise events as the pass-by noises within a sequence stemmed from different perceptual categories of the typology and were presented at different L_{Aeq}. The pass-bys also differed in temporal evolution of loudness (*cf.* Figures 3.5 and 3.6) and were rated differently (*cf.* Figure 3.4).

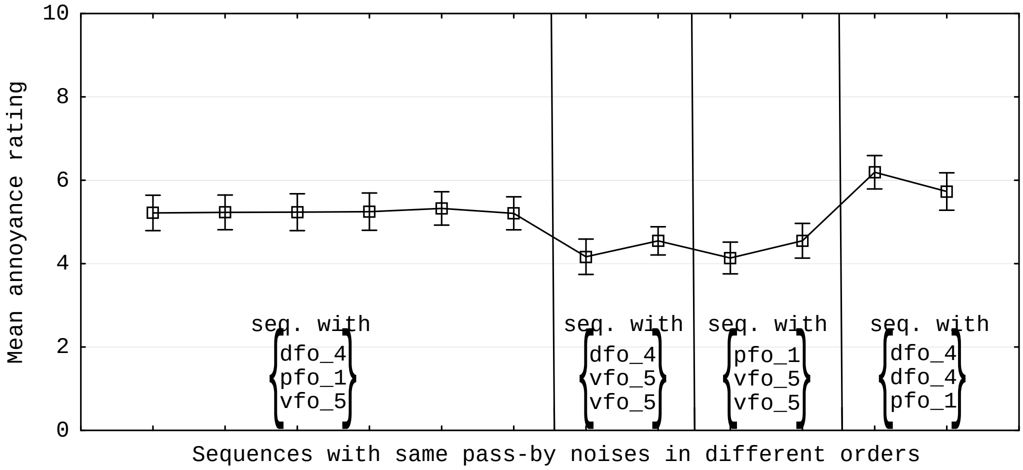

Figure 3.12: Exp. II – Events non-equalized in A-weighted equivalent sound pressure level – Mean annoyance rating as a function of the sequences (denoted by seq.) composed of 3 pass-by noises at constant speed and corresponding standard errors (vertical error-bars).

Finally, according to t-tests, it can be observed that the annoyance ratings of the sequences were inversely correlated with the number of light vehicles appearing within the sequences: sequences without light vehicles were significantly more annoying than sequences with one light vehicle, which were significantly more annoying than sequences with two light vehicles. According to Exp. B and Figure 3.4, the PTW at constant speed (dfo_4) and the heavy vehicle at constant speed (pfo_1) were more annoying than the light vehicle at constant speed (vfo_5). It seems that the vehicle type and the specific annoyance due to these single pass-by noises influenced the total annoyance of the sequence but the order of these different pass-by noises within the road traffic sequence did not have any influence.

5 Discussion

5.1 Influence of the noise events

The experiments were designed to study the influence of acoustical factors which emerged in literature on noise annoyance due to urban road traffic noise (*e.g.* [103]). The studied urban road traffic consisted of PTWs, buses, heavy and light vehicles, as it may be observed in cities.

5.1.1 Influence of the source

Exp. A dealt with annoyance due to different urban road vehicles equalized in L_{Aeq}. The different urban road vehicles led to different annoyance ratings: PTWs were judged among the most annoying pass-by noise sources and light vehicles among the least annoying. Exp. B confirms these expected results, as PTWs are usually cited among the most annoying noise sources (*e.g.* [103, 137]). Exp. I also showed that the noise sequences comprising PTWs were more annoying than the noise sequences with buses and heavy vehicles. The sequences comprising only buses and heavy vehicles were more annoying than the noise sequences with buses, heavy and light vehicles. This result was confirmed by Exp. II (*cf.* Figure 3.12), showing that the noise sequences without light vehicles were judged more annoying than sequences with light vehicles. Exp. I and II indicated that the total annoyance ratings of the sequences seem to be influenced by the specific annoyance of a particular annoying noise event, in the same way as louder elements receive higher weights during global loudness assessment [98]. Considering these results, it seems necessary to pay a particular attention to the PTWs in road traffic noise management. It must be noted that in the recent modified common noise assessment methods [33], the European Commission recommends to consider PTW in a special category of vehicles, thus PTW will no longer be aggregated with the light vehicles.

5.1.2 Influence of the number of events

Exp. I and Exp. II. showed that annoyance increased with the number of vehicles. This result was expected since the influence of the number of noise events, even for noise sequences with similar L_{Aeq}, has been previously highlighted for aircraft noises [66] and for road traffic noises [64]. Furthermore, in the current experiments, an increase in the number of vehicles appearing in one sequence implies an increase of the equivalent sound pressure level of the sequence, which is an important acoustical factor of annoyance. The aim of Exp. II was to compare the results obtained by Björkman [15] with the city traffic studied under laboratory conditions considering different urban vehicles (PTWs, buses, heavy and light vehicles). Björkman [15] showed that annoyance increased with the number of heavy vehicles a day up to a breakpoint of around 2,000 heavy vehicles a day. In Exp. II, the number of vehicles increased from 10 to 50 for 3-minute sequences. Considering the proportion of each vehicle type in the traffic, urban road traffic noise sequences with 1 to 5 heavy vehicles in 3 minutes were tested. This was equivalent to a traffic composed of 480 to 2400 heavy vehicles a day. Figure 3.11 showed that the increase between 10 and 30 vehicles in 3 minutes (*i.e.* between 1 and 3 heavy vehicles in 3 minutes or between 480 and 1440 heavy vehicles a day) is steeper than the increase between 30 and 50 vehicles (*i.e.* between 3 and 5 heavy vehicles in 3 minutes or between 1,440 and 2,400 heavy vehicles a day). The breakpoint in this study seemed therefore to be of the same order of magnitude as the one found by Björkman [15]. However, it should be pointed out that the number of heavy vehicles in the noise sequences increases in the same proportion as the number of light vehicles, the number of PTWs and the total number of vehicles. It is therefore not possible to conclude that the breakpoint observed in Figure 3.11 is only due to the heavy vehicles. It may also be due to the presence of other types of vehicles, in particular PTWs, as they are known to be very annoying.

5.1.3 Influence of the order of the noise events

Since loudness appears to be an underlying basis of judged annoyance [47], confirmed by high correlation between loudness and annoyance [2, 14, 77, 87], it was expected that literature results concerning loudness judgments can also be observed for noise annoyance judgments. For example, the evaluated global loudness of an increasing and a decreasing time-intensity profile with the same maximum sound pressure level is inversely correlated to their steepness [107]. Since the different pass-by noises did not exhibit the same temporal profiles (*cf.* Figures 3.5 and 3.6), we expected the sequences with steeper time-intensity slopes at the beginning of the sequence to be judged less annoying than the sequences with shallower time-intensity slopes. For example, in Exp. I, for pass-by noises equalized in L_{Aeq}, vfo_5 had an increasing slope of 7 dB(A)/s, whereas bfu_3 had an increasing slope of 10 dB(A)/s. Thus, the sequences with bfu_3 at the beginning (3bpv) was expected to be judged less annoying than the sequence with vfo_5 at the beginning (3bpv_bis). But this was not the case. Exp. II with L_{Aeq} differences between vehicles led to the same result: sequences with the same pass-by noises presented in a different order were not significantly different.

Furthermore, studies dealing with the evaluation of loudness for increasing and decreasing time-intensity profiles showed that increasing profiles are judged louder than decreasing profiles [108]. Because of the relation between loudness and annoyance [47, 2, 14, 77, 87], it was expected that sequences with the most annoying (or the loudest) pass-by noise appearing at the end would be judged more annoying than sequences with pass-by noises occurring at the beginning. Three different types of pairs of urban road traffic noise sequences were studied:

- Sequences differing only in the order of pass-by noises with same L_{Aeq} but with different specific annoyance ratings (rated in Exp. A) led to the same total annoyance judgment in Exp. I. (*e.g.* 3bpv compared to 3bpv_bis; bfu_3 and vfo_5 had the same L_{Aeq}, but bfu_3 was judged more annoying than vfo_5 (*cf.* Figure 3.1));
- Sequences differing only in the order of pass-by noises with the same specific annoyance but different L_{Aeq} led to the same annoyance judgment in Exp. II. (*e.g.* dfo_4+dfo_4+pfo_1 compared to pfo_1+dfo_4+dfo_4; the two pass-by noises dfo_4 and pfo_1 did not have the same L_{Aeq} but were equally annoying (*cf.* Figure 3.4));
- Sequences differing only in the order of pass-by noises with different specific annoyance ratings and different L_{Aeq} led to the same total annoyance judgment in Exp. II. (*e.g.* dfo_4+vfo_5+vfo_5 compared to vfo_5+vfo_5+dfo_4; the two pass-by noises dfo_4 and vfo_5 did not have the same L_{Aeq} neither the same specific annoyance (*cf.* Figure 3.1)).

Both Exp. I and Exp. II led to the conclusion that sequences with the same pass-by noises presented in a different order were not significantly different. It seems that annoyance evoked by an urban road traffic sequence was determined by the presence of a noticeable event in the sequence instead of its position within the sequence. This result supports the findings of Schreiber and Kahneman [121]: the most annoying part of a negative episode influences its retrospective judgment. This hypothesis was confirmed by the verbalizations of the participants who noticed the presence of particularly annoying pass-by noises: *"the aggressive sounds are the mopeds and the trucks."* (*"les sons agressifs, ce sont les mobylettes et les camions".*)

5.2 Influence of the quiet periods

Exp. I showed that the urban road traffic noise sequences with quiet periods were significantly less annoying than the ones without quiet periods. However, Exp. I showed that the quiet period duration between noise events (3 or 6 seconds) and the cumulative quiet period duration within the sequence did not have any effect on noise annoyance. For example, regarding 4-event sequences, the sequences D2 and D1 had a quiet period duration between noise events of 3 seconds and 6 s, respectively, and a cumulative quiet period duration of 9 s and 18 s, respectively. Despite these differences, the annoyance ratings of these sequences were not significantly different.

Moreover, several studies on the evaluation of global loudness showed that the beginning [30, 104] and/or the end [30, 104, 123] of a stimulus influence loudness judgments more than the middle of the stimulus. According to Dittrich and Oberfeld [30], the influence of the end of a stimulus is more pronounced when the loudness of the end corresponds to the maximum loudness of the sequence. Considering these results, it was hypothesized that the position of the quiet period within the sequence may have an effect on annoyance ratings. For example, it was hypothesized that noise sequences with quiet periods at the beginning (*i.e.* D4 and D7) or at the end of the sequences (*i.e.* D3 and D6) would be judged less annoying than sequences of the same duration but with noise events at the beginning and at the end (*i.e.* D1). Exp. I showed that this hypothesis was not confirmed: sequences with different positions of quiet periods did not get significantly different annoyance ratings.

It should be noted that studies dealing with loudness judgments usually consider artificial noise sequences [30, 104, 108, 107] or sounds of accelerating vehicles recorded inside the vehicles [123]. The sequences studied in this paper were very different as they contained several pass-by noises, each having one increasing and one decreasing time-intensity slope. Furthermore, other temporal features (*e.g.* the slope of the signal envelope, *cf.* [103]) or spectral features (*cf.* [91]) contributed to the annoyance judgment of the different pass-by noises of the sequence. In addition, the sequences implied cognitive phenomena, since the pass-by noises were real sounds experienced everyday by participants (*cf.* [90, 87]). The complexity of these sequences may partly explain the differences observed between the results and the hypothesis derived from findings concerning loudness and based on the fact that loudness appears to be an underlying basis of judged annoyance [47], dominant over the other acoustical features [20].

6 Conclusion

The objective of this work was to study the influence of different acoustical factors on annoyance due to urban road traffic composed of different urban road vehicles (PTWs, buses, heavy and light vehicles). The experiments led to the following results:

– The type of vehicle and the number of pass-by noises explained an important part of the variance in annoyance judgments: the PTWs, buses and the heavy vehicles are more annoying than the light vehicles. This shows the importance to consider PTWs in further studies dealing with urban noise environments (*e.g.* soundscapes or road traffic modeling) and particularly with noise annoyance due to urban road traffic.
– It seems that noise annoyance due to an urban road traffic comprising PTWs increased with the number of vehicles, up to a breakpoint, after which it saturated and increased more slowly.
– The order of the different urban vehicle pass-by noises (PTWs, buses, heavy and light vehicles) within an urban road traffic sequence had no influence on annoyance.
– It seems that participants' ratings were more influenced by the presence of a very specific pass-by noise rather than by its position. The latter result, expressed in terms of specific annoyance due to noise events and its relation to annoyance due to successive noise events, may be of interest for combined noise source studies dealing

with different transportation noise events and the understanding of dominance effects.
- The presence of quiet periods in an urban road traffic noise sequence decreased annoyance, compared to sequences without quiet periods.
- The position of quiet periods and their cumulative duration had no influence on annoyance ratings of sequences composed of the same pass-by noises.

These different results highlighted in this work contribute to i) the understanding of the influence of the studied acoustical factors on noise annoyance due to urban road traffic with PTWs, ii) and to the perspective of enhancing noise annoyance models.

Résumé des principaux résultats

♣ Le type de véhicule et le nombre de bruits de passage expliquent une part importante de la variance des jugements de gêne de court-terme : les deux-roues motorisés, les bus et les poids-lourds sont plus gênants que les véhicules légers. Ce résultat montre l'importance de considérer les deux-roues motorisés comme une catégorie à part entière dans les études portant notamment sur la gêne due au bruit de trafic routier urbain.
♣ La gêne due à un trafic routier urbain comprenant des deux-roues motorisés semble augmenter avec le nombre de véhicules jusqu'à un seuil, après lequel la gêne augmente plus lentement.
♣ Le jugement des participants semble être plus influencé par la présence d'un bruit de passage spécifique plutôt que par la position de ce bruit de passage au sein de la séquence sonore, puisque l'ordre des bruits de passage n'influence pas la gêne.
♣ La présence de périodes de calme dans un bruit de trafic routier urbain diminue la gêne sonore, mais la position et la durée cumulée de ces périodes de calme n'ont pas d'influence sur la gêne sonore.

Et après ?

Ce chapitre a montré l'importance de prendre en compte la présence des deux-roues motorisés au sein de séquences de trafic routier urbain. L'ordre des bruits de passage des véhicules routiers urbains et la position des périodes de calme au sein d'une séquence sonore n'ont pas à être considérés lors de la construction de séquences sonores pour l'évaluation de la gêne en conditions contrôlées.

Les résultats obtenus dans ce chapitre seront utilisés pour construire les séquences de bruit de différentes compositions de trafic routier urbain étudiées aux Chapitres 4 et 5. Ils faciliteront également l'analyse des résultats du Chapitre 4, puisque l'influence (ou l'absence d'influence) de certains facteurs acoustiques sur la gêne de court-terme due au bruit de trafic routier urbain a été démontrée dans ce chapitre.

Le Chapitre 4 sera ainsi dédié à la caractérisation physique et perceptive du bruit de différentes compositions de trafic routier urbain du point de vue de la gêne de court-terme, étudiée en conditions contrôlées.

Chapitre 4

Caractérisation physique et perceptive du bruit de trafic routier urbain pour différentes compositions de trafic

*Ce chapitre est composé d'un article soumis à un journal international à comité de lecture. Il est intitulé **"Noise sensitivity and loudness derivative index for urban road traffic noise annoyance computation"**. Il est co-écrit avec Catherine Marquis-Favre et Reinhard Weber. La collaboration de Reinhard Weber a porté sur l'adaptation du calcul des indices m_{sputt} et m_{nas} aux bruits routiers urbains entendus en présence d'un bruit de fond urbain.*

Questions scientifiques

Les questions auxquelles nous souhaitons répondre dans ce chapitre sont les suivantes :

- ♣ Quels sont les facteurs acoustiques qui influencent la gêne de court-terme due au bruit de trafic routier urbain ?
- ♣ La part de chaque type de véhicule dans le trafic routier urbain a-t-elle une influence sur les notes de gêne ?
- ♣ Quels indices permettent de caractériser les facteurs acoustiques influant la gêne due au bruit de trafic routier urbain ?
- ♣ La sensibilité des participants de l'expérience permet-elle d'expliquer une part de la gêne de court-terme due au bruit de trafic routier urbain ?

Une expérience avec mise en situation a été réalisée, au sein de laquelle les participants ont évalué la gêne due à des séquences sonores de trafic routier urbain comprenant des deux-roues motorisés. Le nombre de passages de véhicules et la répartition des différents types de véhicules varient au sein de ces séquences sonores. Ce chapitre utilise les résultats du Chapitre 3 pour la construction des séquences sonores et les résultats du Chapitre 2 pour améliorer les modèles de gêne en considérant des facteurs acoustiques et non-acoustiques.

Abstract

Urban road traffic composed of powered-two-wheelers, buses, heavy and light vehicles is a major source of noise annoyance. In order to enhance annoyance models considering different acoustical and non-acoustical factors, a laboratory experiment on short-term annoyance due to urban road traffic noise was conducted. At the end of the experiment, participants were asked to rate their noise sensitivity and to describe the noise sequences they heard. This verbalization task highlights that annoyance ratings are highly influenced by the presence of powered-two-wheelers and by different acoustical features: noise intensity, irregular temporal amplitude variation, regular amplitude modulation and spectral content. These features, except irregular temporal amplitude variation, are satisfactorily characterized by the loudness, the total energy of tonal components and the sputtering and nasal indices. Introduction of the temporal derivative of loudness as a new index allows successful modeling of perceived amplitude variations. Its contribution to the tested annoyance models is high and seems to be higher than the contribution of mean loudness index. A multilevel regression is performed to test different relevant combinations of noise indices to enhance annoyance models considering noise sensitivity too. Three combinations of noise indices coupled with noise sensitivity are found to be promising for further studies that aim to enhance current annoyance models.

Introduction

Annoyance is one of the most widespread non-acoustical effects of noise exposure for non-critical noise level and the most cited annoying noise source is the road traffic [51]. According to the European directive 2002/49/EC [70], European cities of more than 100,000 inhabitants produce strategic noise maps for several environmental noise sources, such as road traffic noise. These maps characterize noise exposure using the energy-based index L_{den} – the day-evening-night level. This index is also used in relationships recommended by the European Commission for noise annoyance prediction [70]. However, different studies showed that these relationships did not allow a good prediction of noise annoyance measured during recent socio-acoustical surveys (*e.g.* [42]). Actually, several studies demonstrated that such energy-based index explains only a small part of the whole variance in noise annoyance (*e.g.* [57]). Indeed, noise annoyance is further influenced by numerous acoustical features (*e.g.* amplitude fluctuations, rise time of sound, spectral distribution of energy [77]) as well as by non-acoustical factors (*e.g.* noise sensitivity [140, 130, 133, 116]).

Several studies contributed to enhance noise annoyance modeling by improving the characterization of acoustical features of noise influencing annoyance. For example, characterization of perceived noise intensity may be improved by the use of loudness (denoted as N, as recommended in the ISO standard 1996 [52]) instead of sound pressure level. Studying noise annoyance due to powered-two-wheelers (PTWs), Vos [137] demonstrated that correlation between annoyance and N_5 (loudness that is exceeded in 5% of the duration, *cf.* Chapter 1, Section 2.3.1.4) is slightly higher than correlation between annoyance and A-weighted sound exposure level. Indeed, loudness index is closer to perceived noise intensity than sound pressure level, as it considers spectral and temporal masking effects of auditory signal processing (*cf.* [34]).

Concerning irregular temporal amplitude variations, Griffiths and Langdon [44] studied *in situ* dissatisfaction due to urban road traffic noise. They found that taking into account more than one measure for the characterization of noise level improved the correlation with the mean dissatisfaction rating. They proposed the "Traffic Noise Index" (denoted as TNI, *cf.* Chapter 1, Section 2.3.5.1), composed with the 10^{th} and the 90^{th} percentile sound pressure levels: this index is thus related to the noise level as well as to its variation. Furthermore, for aircraft noise, Muller [94] introduced another index to take into account the same acoustical features: the corrected equivalent noise level, L'_{eq}, calculated as a function of the equivalent sound pressure level L_{eq} and its variation as a function of time, denoted as σ' (*cf.* Chapter 1, Section 2.3.5.3). This index was also used regarding simulated [112] and recorded [139] highway traffic noise and it showed a good correlation with annoyance ratings. Several authors used specific indices to characterize amplitude variation due to transportation pass-by noise as this acoustical feature is known to have a negative impact on hedonic judgments (*e.g.* [3, 126]) and to be correlated with annoyance (*e.g.* [25, 91]). Trollé *et al.* [130, 131] employed the variance of time-varying A-weighted pressure normalized by RMS A-weighted pressure (denoted as VAP, *cf.* Chapter 1, Section 2.3.2.1) to characterize the irregular/continuous character of the overall pressure rise of tramway pass-by noises. Klein [60] applied the standard deviation of time varying A-weighted pressure (denoted as $STDP$, *cf.* Chapter 1, Section 2.3.2.2) to characterize irregular amplitude variations of urban road vehicle pass-by noises. Both indices well correlated with annoyance.

Concerning spectral content, several studies dealing with transportation noise annoyance (*e.g.* tramway [130, 131], urban road vehicle [61]) showed that spectral content is mentioned by participants to describe noises ("*shill/dull*", "*metallic*", "*treble*", "*squealing*"). Klein *et al.* [61] noted that participants referred their annoyance judgments to spectral content of urban road vehicle pass-by noises. Studying tramway noise annoyance, Trollé *et al.* [130, 131] proposed a new psychoacoustical index: the total energy of the tonal components within a critical band range (denoted as $TETC_{x-y}$, *cf.* Chapter 1, Section 2.3.4.2). It is used to characterize the bass/treble character of tramway noises. This index was also found to be relevant for the annoying sensation evoked by spectral content of urban road vehicle pass-by noises by Klein *et al.* [61].

Amplitude modulation also influences annoyance due to urban road vehicle noise [93, 61, 103]. Indeed, studying urban road vehicle pass-by noises, Morel *et al.* [93] and Klein *et al.* [61] showed that participants noted the presence of amplitude modulation-related sensations ("*snoring*", "*purring*", "*nasal*", "*sputtering*"). As an outcome of a free categorization task, Morel *et al.* [93] proposed a perceptual typology of urban road vehicle pass-by noises. For each perceptual category, Morel *et al.* [91] presented annoyance models involving roughness (denoted as R, *cf.* Chapter 1, Section 2.3.3.1) and fluctuation strength (denoted as F, *cf.* Chapter 1, Section 2.3.3.1) for PTWs in acceleration and deceleration, and for buses, heavy and light vehicles in deceleration. In their *in situ* study, Paviotti and Vogiatzis [103] concluded that roughness cannot constistently explain annoyance due to PTW. Based on these results, Klein *et al.* [61] performed a semantic differential test for urban road vehicle pass-by noises under laboratory conditions. They found that roughness and fluctuation strength were not meaningful to account for the "sputtering" and the "nasal" modulation-related sensations. Furthermore, both indices were not correlated with annoyance ratings, whereas participants reported a relationship between annoyance and these modulation-related sensations. On the basis of modulation spectra, Klein *et al.* [61] proposed the "sputtering" and the "nasal" indices (denoted as $m_{\mathrm{sputt},10}$ and $m_{\mathrm{nas},10}$, *cf.* Chapter 1, Section 2.3.3.2) to provide a description for these sensations.

As noise annoyance is influenced by additional acoustical features of the noise, some annoyance models using quite a number of indices were proposed. For example, Fastl and Zwicker [34] proposed the "Psychoacoustic Annoyance" model (denoted as PA, *cf.* Chapter 1, Section 2.3.5.4), based on loudness, sharpness (denoted as S, *cf.* Chapter 1, Section 2.3.4.1), fluctuation strength and roughness indices. This model was used to predict annoyance ratings for car pass-by noise and showed a good predictive potential. Klein *et al.* [61] introduced the "Urban Road vehicle pass-by noise Annoyance" model (denoted as URA, *cf.* Chapter 1, Section 2.3.5.5) for urban road vehicle pass-by noise including PTW. This model is based on N, $TETC$, $m_{\text{sputt},10}$ and $m_{\text{nas},10}$.

Finally, as annoyance is also influenced by non-acoustical factors and in particular by noise sensitivity (*e.g.* [125, 54, 99], *cf.* Chapter 2), several authors employed noise sensitivity in annoyance models (*e.g.* [84, 5, 130, 131]). For example, Trollé *et al.* [130, 131] proposed an annoyance model for tramway noise using multilevel regression: noise sensitivity of participants was introduced as an explanatory variable at individual level and different noise indices at stimulus level.

There is a long-term need to improve noise annoyance prediction. The aim of the present study is to contribute to these long-term requirements by proposing indicators based on noise sensitivity and on acoustical and psychoacoustical indices in order to account for different acoustical factors. In the present study, we consider different compositions of urban road traffic noise, with PTWs, buses, heavy and light vehicles. The main objective is to enhance annoyance model by considering noise sensitivity and additional acoustical features. Short-term annoyance is evaluated under laboratory conditions for different compositions of urban road traffic noise. After identifying different influential acoustical features, different indices are tested in order to take these acoustical features into account. Then, multilevel regression is considered in order to use noise sensitivity as an explanatory variable at individual level and relevant indices at stimulus level. Multilevel regression analysis allows the identification of different promising combinations of noise indices coupled with noise sensitivity to calculate noise annoyance.

1 Method

This experiment aims to assess short-term annoyance in laboratory conditions due to different compositions of urban road traffic noise, with PTWs, buses, heavy and light vehicles.

1.1 Stimuli

For the experiment, 27 urban road traffic noise sequences were constructed using different urban road vehicle pass-by noises and an urban background noise. The noises were recorded using ORTF technique in accordance with French standards, to enable a good sound reproduction (*cf.* [93]).

The sound pressure level differences between the single pass-by noises were according to equivalent sound pressure levels measured *in situ* (*cf.* [61]) for the different types of vehicles studied (PTWs, buses, heavy and light vehicles) and their driving conditions in urban areas (acceleration, deceleration, constant speed). A-weighted equivalent sound pressure level (L_{Aeq}) of single pass-by noises ranged from 53.5 dB(A) to 67.1 dB(A). The background noise was equalized at 40 dB(A), in order to be masked by the pass-by noise with the lowest L_{Aeq}.

Urban road traffic noise sequences were constructed in order to reproduce urban road traffic compositions measured in inner Paris at different hours of working days (*cf.* [75]). Sequences were 3 minutes long. Such a stimulus duration allows the study of different vehicles at different driving conditions (acceleration, deceleration, constant speed). Sequences comprise between 16 and 80 vehicles, with varying percentages of PTWs from 8% to 44% (*cf.* [75]) and varying percentages of buses and heavy vehicles (BHVs) from 3% to 10% (*cf.* [75]). They simulated one-way or two-way roads. They were constructed with and without overlaps between the pass-by noises. The overlap is due to the fact that certain pass-by noises ended after the next one started. Table 4.1 gives traffic composition and L_{Aeq}[1] of each urban road traffic noise sequence. The traffic noise sequences are denoted as xTy, x for the way road number and y an arbitrary number to differentiate between the traffic compositions. For example, the traffic noise sequences 1Ty and 2Ty present the same percentage per type of vehicles, but there are twice more vehicles in 2Ty than in 1Ty.

The construction of urban road traffic noise sequences took into account the results of a previous study (*cf.* Chapter 3, Sections 3.2 and 4.2): i) presence of quiet periods in an urban road traffic noise sequence decreases annoyance, compared to sequences without quiet periods, ii) temporal position of quiet periods and their cumulative duration have no influence on annoyance and iii) short-term annoyance due to urban road traffic sequence appears to be due to the presence of a noticeable event in the sequence instead of its temporal position within the sequence. Thus, sequences were constructed without consideration for temporal position of quiet periods and of different vehicles within the sequences.

No filter simulating facade transmission was applied to the stimuli as wall material and window types have an effect on auditory judgments [128] and the choice of one specific kind of facade might have been too limiting. Thus, the worst noise exposure is considered (*e.g.* [2]) such as being in private outdoor spaces near urban road.

1.2 Apparatus

The experiment took place in a quiet room with a background noise of 19 dB(A). The stimuli were reproduced employing a 2.1 audio reproduction system consisting of two active loudspeakers and one active subwoofer. Concerning the positioning of participant and loudspeakers, the center of the interaural axis of the participant and the loudspeakers formed an equilateral triangle. This was in accordance with recommendations given by Bech and Zacharov [7]. The loudspeakers were placed at a height of 1.20 m from the floor, and the subwoofer was placed on the floor between the loudspeakers. An artificial head and an omnidirectrional microphone were placed at the participant's position in order to record the noise sequences.

1.3 Procedure

Participants were asked to imagine themselves at home while relaxing during a reading activity. They could bring along their own reading stuff for the experiment. This procedure has been used in previous works (*e.g.* [89]). Prior to each experiment, participants were

1. L_{Aeq} is calculated over the duration of the noise sequence, *i.e.* over 3 minutes.

Table 4.1: Three-minute urban road traffic noise sequences. Light vehicles, buses and heavy vehicles and PTWs are respectively denoted LV, BHV and PTW.

Sequence labelling	Number of vehicles	Number of LV	BHV	PTW	Percentage of LV	BHV	PTW	L_{Aeq} dB(A)
				ONE-WAY WITHOUT OVERLAP				
1T1	16	11	1	4	69 %	6 %	25 %	57,4
1T2	18	11	1	6	61 %	5 %	34 %	58,6
1T3	19	11	1	7	58 %	5 %	37 %	58,8
1T4	20	13	1	6	65 %	5 %	30 %	58,5
1T5	20	16	1	3	80 %	5 %	15 %	57,3
				TWO-WAY WITHOUT OVERLAP				
2T1	32	22	2	8	69 %	6 %	25 %	60,3
2T2	36	22	2	12	61 %	5 %	34 %	61,4
2T3	38	22	2	14	58 %	5 %	37 %	61,8
2T4	40	26	2	12	65 %	5 %	30 %	61,4
2T5	40	32	2	6	80 %	5 %	15 %	60,2
				ONE-WAY WITHOUT OVERLAP				
1T6	24	20	2	2	84 %	8 %	8 %	57,9
1T7	27	14	1	12	52 %	4 %	44 %	60,7
1T8	28	24	1	3	86 %	3 %	11 %	57,9
1T9	31	23	3	5	74 %	10 %	16 %	60,0
1T10	36	29	1	6	80 %	3 %	17 %	59,8
1T11	40	31	1	8	77 %	3 %	20 %	60,5
				TWO-WAY WITH OVERLAP				
2T6	48	40	4	4	84 %	8 %	8 %	60,9
2T7	54	28	2	24	52 %	4 %	44 %	63,5
2T8	56	28	2	6	86 %	3 %	11 %	60,9
2T9	62	26	6	10	74 %	10 %	16 %	63,1
2T10	72	58	2	12	80 %	3 %	17 %	62,7
2T11	80	62	2	16	77 %	3 %	20 %	63,7
				ONE-WAY WITH OVERLAP				
1T12	43	31	2	10	72 %	4 %	23 %	61,4
1T13	44	25	2	17	56 %	5 %	38 %	63,2
1T14	45	28	2	15	62 %	5 %	33 %	63,0
1T15	47	38	1	8	81 %	2 %	17 %	61,1
1T16	50	30	2	18	60 %	4 %	36 %	63,1

trained. During the training and the experiment, the stimuli were presented one by one in random order.

After each stimulus, a reminder of the imaginary situation was presented to participants and they were asked: "*During your relaxing activity, you hear this noise. Does this noise annoy you?*". Participants gave the ratings on a continuous scale ranging from "0" to "10", with 11 evenly spaced numerical labels and two verbal labels at both ends ("*not at all*" and "*extremely*").

At the end of the experiment, participants performed a verbalization task [2]: they answered the two following questions: "*Can you tell what you thought about the road traffic noise?*" and "*If you have found some noise sequences annoying, can you tell us why you*

2. The questionnaire is similar to the one given in Appendix A, Section 1, with only questions relative to urban road traffic noise.

found them annoying?". If the first answer was very short, the experimenter asked three supplementary questions after the first one, in order to obtain more descriptions from the participant: "*Did the road traffic noise seem to be familiar to you?*", "*Can you describe the road traffic noise?*" and "*In a general way, how do you judge road traffic noise?*". Then, they filled in a questionnaire with personal items such as non-acoustical factors. For noise sensitivity, participants were asked: "*Would you say you are sensitive to noise in a general way?*" and they had to make a judgment on a continuous scale ranging from "0" to "10" with two verbal labels at both ends ("*not at all sensitive*" and "*extremely sensitive*"). The experiment was lasting for two hours.

1.4 Participants

The experiment was performed by 34 participants (16 male, 18 female) aged between 20 and 55 years (mean age = 32.3; standard deviation = 12.7). All participants declared normal hearing abilities and were paid for their participation. 65 % of the participants declared no difficulty to perform the test.

2 Results

In this section, the results are presented, with the objective to enhance noise annoyance model. First, influential acoustical features of urban road traffic noise on annoyance are to be identified on the basis of the verbalizations the participants made. Second, correlation analysis between annoyance ratings, existing indices and annoyance models considering these acoustical features is carried out to characterize the influential acoustical features previously highlighted. Finally, multilevel regression is used to consider acoustical and non-acoustical variables in noise annoyance models.

2.1 Description of the verbalizations

All participants mention the presence of PTWs ("*motorbikes*", "*mopeds*", "*scooter*") whereas 53% of the participants mention light vehicles ("*light vehicle / car*") and only one third mention BHVs ("*heavy vehicle*", "*bus/truck*"). Furthermore, 91% of the participants explicitly associate PTWs to annoyance ("*Motorbike noises were very annoying*").

Participants make negative judgments on PTWs, because of : i) their spectral acoustical features (21% of the participants), ii) their modulated amplitude (18% of the participants) and iii) their driving condition (15% of the participants).

Regarding spectral acoustical features, a typical statement is : *"Most annoying noises were deep or shrill motorbikes"*. Explaining why some noise sequences are annoying with respect to amplitude modulation, a participant remarks *"the little moped that made a sound like a bee"*. Specific driving conditions of PTWs get particular attention : *"Horrible, the PTW noise, equally when accelerating or decelerating"*.

It is interesting to note that 56% of the participants mention perceived noise intensity (*e.g. "loud"* - 9 occurrences or *"noisy"* - 4 occurrences) and temporal amplitude variations (*e.g. "quiet period and noise alternating"*), whereas 24% of the participants characterize spectral content (*e.g. "shrill"* - 8 occurrences or *"deep"* - 4 occurrences) and 6% mention modulation-related sensations (*"nasal"* -1 occurrence). Indices characterizing these acoustical features are candidates to partly explain noise annoyance ratings.

2.2 Characterization of the highlighted acoustical features

Figure 1 displays mean annoyance ratings with clear differences obtained for different urban road traffic noise sequences tested. First, it seems that annoyance ratings increase with the number of vehicles: 1T1 (16 vehicles) is significantly less annoying than 1T16 (50 vehicles). However, additional features also influence annoyance ratings. For example, two sequences with the same number of vehicles (*e.g.* 2T4 and 2T5 with 40 vehicles) but with different traffic compositions (in 2T4, 30% of PTWs and in 2T5, 15% of PTWs) obtain significantly different noise annoyance ratings. This occurs when the number of BHVs is the same (*e.g.* 5% in the example of 2T4 and 2T5 comparison) and the number of PTWs varies. However, 1T4 and 1T5 presenting the same traffic compositions in terms of percentages as 2T4 and 2T5, respectively, are not significantly different. Thus, it turns out that urban road traffic composition in terms of number of different types of vehicle has a significant influence on annoyance ratings and that there is an interaction effect of the number of PTWs and of the total number of vehicles on noise annoyance.

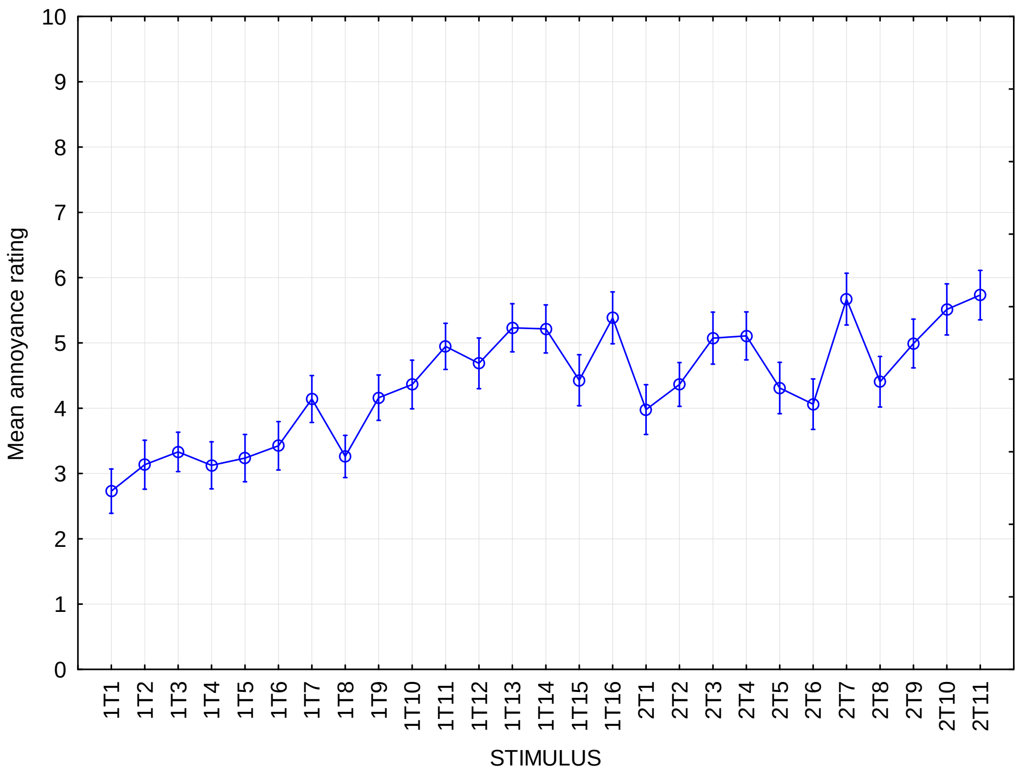

Figure 4.1: Mean annoyance rating for all traffic noise sequences ordered according to the labels in Table I. The vertical error-bars represent the standard errors.

To explain observed differences and to investigate the relationship between selected noises indices and mean annoyance ratings, Bravais-Pearson correlation coefficients r are calculated. These correlations support the interpretation of acoustical features mentioned by participants (*cf.* Section 2.1). First, correlations between annoyance ratings and different indices used in literature to characterize these acoustical features are computed [3]. Main indices are presented in Table 4.2: A-weighted equivalent sound pressure level L_{Aeq}, loudness N, temporal derivative of sound pressure level σ' (*cf.* [94] and Chapter 1, Section 2.3.5.3), variance of the A-weighted pressure VAP [130, 131], standard deviation of the time varying A-weighted sound pressure $STDP$ [60], total energy of tonal components $TETC$ within critical bands from 16 to 24 Barks [61], sharpness S, roughness R, fluctuation strength F, sputtering and nasal indices $m^*_{\text{sputt},10}$ and $m{*}_{\text{nas},10}$ [61].

These last two indices are extensions of the sputtering and the nasal indices that were introduced by Klein *et al.* [61] to characterize specific features of modulated urban road vehicle pass-by noises [61]. As unmodulated urban background noise is also used in the experiment, the calculation of the sputtering and nasal indices is adjusted to the unmodulated parts within noise sequences.

The original calculation of the sputtering and nasal modulation index is based on the calculation of the modulation indices within one time frame i:

$$m_{sputt_i} = \left[\frac{2 \times |P_{\max}(2\ Hz - 100\ Hz)|}{P(0)}\right]_i \tag{4.1}$$

$$m_{nasal,i} = \left[\frac{2 \times |P_{\max}(100\ Hz - 200\ Hz)|}{P(0)}\right]_i \tag{4.2}$$

where P denotes the spectrum of the envelope of noise in the time frame i with the DC value $P(0)$, the maximal modulation amplitude $|P_{\max}(2\ Hz - 100\ Hz)|$ in the modulation frequency region from 2 Hz - 100 Hz and the maximal modulation amplitude $|P_{\max}(100\ Hz - 200\ Hz)|$ in the modulation frequency region from 100 Hz - 200 Hz. For unmodulated noise, the DC value $P(0)$ turns out to be very small. So, its size is used as a decision criterion between modulated and unmodulated parts of noise when calculating modulation indices. Extended modulation indices for time frames i of modulated and unmodulated noise are defined in the following way:

$$m^*_{sputt_i} = \left[\begin{array}{rl} m_{sputt_i}, & \text{if} \quad P(0Hz) > P_{crit} \\ 0, & \text{if} \quad P(0Hz) < P_{crit} \end{array}\right. \tag{4.3}$$

$$m^*_{nasal_i} = \left[\begin{array}{rl} m_{nasal_i}, & \text{if} \quad P(0Hz) > P_{crit} \\ 0, & \text{if} \quad P(0Hz) < P_{crit} \end{array}\right. \tag{4.4}$$

where P_{crit} is a critical amplitude to separate modulated from unmodulated frames. These indices have therefore no unit and their values range from 0 to 1. In the same way as was proposed by Klein et al. [61], the sputtering and nasal indices are the 90% percentiles of the modulation amplitudes that are exceeded in 10% of the time: $m^*_{sputt_i}$ and $m^*_{nasal_i}$.

In addition to the temporal derivative of the sound pressure level σ'[94], the temporal derivative of loudness $\sigma'(N)$ is introduced in the current work as a more psychoacoustically motivated sound parameter to characterize loudness variations. More precisely, $\sigma'(N)$ is

3. All the tested indices are not presented hereafter. For example, the number of heavy vehicles (highlighted in literature to be correlated with noise annoyance, *cf.* Chapter 1, Section 2.2.2) or the number of PTWs were significantly correlated with annoyance, but not displayed in Table 4.2 as some other indices were better correlated and as their combination with other indices was not relevant.

the rms of the temporal derivative of loudness:

$$\sigma'(N) = \sqrt{\frac{1}{T}\int_0^T \left(\frac{dN(t)}{dt}\right)^2 dt} \tag{4.5}$$

where $N(t)$ is the loudness as a function of time and T is the duration of the noise sequence, here 3 minutes.

Table 4.2: Bravais-Pearson correlation coefficient r between noise annoyance ratings and indices: L_{Aeq} - A-weighted energy equivalent sound pressure level ($L_{\text{Aeq}} \in$ [56.9;63.8] dB(A)), N - Zwicker loudness energy ($N \in$ [4.7; 9.6] Sone), σ' - temporal derivative of sound pressure level ($\sigma' \in$ [2.1; 32.1] dB(A)/s), $\sigma'(N)$ - temporal derivative of loudness N ($\sigma'(N) \in$ [29.0; 51.2] Sone/s), VAP - variance of the A-weighted sound pressure ($VAP \in$ [0.0068; 0.0115] dB(A)), $STDP$ - standard deviation of the time varying A-weighted pressure ($STDP \in$ [0.0089; 0.0180] dB(A)), $TETC$ - total energy of tonal components within critical bands from 16 to 24 Barks ($TETC \in$ [65.9; 76.5] dB), S - sharpness ($S \in$ [1.10; 1.34] acum), R - roughness ($R \in$ [19.40; 28.40] cAsper), F - fluctuation strength ($F \in$ [8.0; 14.0] cVacil), $m^*_{\text{sputt},10}$ - modulation index to characterize the "sputtering" aspect of the noise ($m^*_{\text{sputt},10} \in$ [0.12; 0.19]), $m*_{\text{nas},10}$ - modulation index to characterize the "nasal" aspect of the noise($m^*_{\text{nas},10} \in$ [0.08; 0.12]). (^{a}: p<0.001, ^{b}: p<0.01, ^{c}: p<0.05)

	L_{Aeq}	N	σ'	$\sigma'(N)$	VAP	$STDP$
r	0.94^a	0.96^a	-0.004	0.96^a	-0.15	0.92^a
	$TETC$	S	R	F	$m^*_{\text{sputt},10}$	$m^*_{\text{nas},10}$
r	0.64^a	0.92^a	0.94^a	0.65^a	0.64^a	0.53^a

Correlations between annoyance and the energy-based index L_{Aeq} and N are the highest ones, as previously found in several studies (*e.g.* [137]). Moreover, σ' and VAP are not correlated with annoyance, whereas $\sigma'(N)$ and $STDP$ are highly correlated with annoyance. $TETC$ and the modulation-related indices are correlated with annoyance, too.

Correlations between annoyance and indicators that are constructed using several indices, are shown in Table 4.3: the traffic noise index TNI [44] which takes into account the 10^{th} and the 90^{th} percentile sound pressure level, the psychoacoustic annoyance model PA [34] which takes into account N, R, F and in some conditions, S and the urban road vehicle pass-by noise annoyance model URA [61] which takes into account N, $TETC$, $m^*_{sputt,10}$ and $m^*_{nasal,10}$.

Table 4.3: Bravais-Pearson correlation coefficient r between noise annoyance ratings and complex indicators: TNI - traffic noise index [44] (TNI $\in$ [72.7; 113.7] dB(A)), PA - psychoacoustic annoyance model [34] (PA $\in$ [11.30; 20.11]) and URA - urban road vehicle pass-by noise annoyance model [61], constructed using several indices (URA $\in$ [4.04; 6.77]). (^{a}: p<0.001, ^{b}: p<0.01, ^{c}: p<0.05)

	TNI	PA	URA
r	-0.62^a	0.84^a	0.96^a

TNI is negatively correlated with annoyance. Indeed, the difference between L_{10} and L_{90} is higher for weak traffic density than for high traffic density, leading to a higher TNI value. Contrary to TNI, PA and URA are highly and positively correlated with annoyance. Calculation of PA does not account for spectral content as the sharpness values are inferior to 1.75 acum (*cf.* [34]). As URA is taking into account spectral features mentioned by participants (*cf.* Section III.A) and is significantly better correlated with annoyance, URA is considered in the following for the construction of an annoyance model.

2.3 Noise annoyance models based on multilevel regression

In order to consider acoustical and individual data in annoyance models, multilevel regression analysis is performed. This regression method has been previously used for meta-analysis of *in situ* transportation noise annoyance studies without explanatory variable at individual level [82] and for modeling annoyance data collected in laboratory conditions for tramway noises [130, 131] with explanatory variable at individual level. Application of multilevel regression on data collected in the current study allows the consideration of both different acoustical features previously highlighted and noise sensitivity. The benefit considering acoustical and non-acoustical variables in road traffic noise annoyance models is assessed. Multilevel regression is briefly presented hereinafter (for more details, see [130, 49, 131]).

Model specification: As data are obtained from a repeated measure experiment, the first level of the regression refers to stimuli (urban road traffic noise sequence, denoted as i in subscript) and the second level refers to the individuals (denoted as j in subscript). Considering a model with one variable at individual level (noise sensitivity, denoted as $Sens$) and M variables at stimulus level (denoted as $Index_m$), the formulas are as follows:

$$A_{ij} = \pi_{0j} + \sum_{m=1}^{M} \pi_{mj} Index_{mi} + e_{ij} \tag{4.6}$$

$$\pi_{0j} = \beta_{00} + \beta_{01} \times Sens_j + u_{0j} \tag{4.7}$$

$$\pi_{mj} = \beta_{m0} + \beta_{m1} \times Sens_j + u_{mj} \tag{4.8}$$

$$\begin{bmatrix} u_{0j} \\ \vdots \\ u_{mj} \\ \vdots \\ u_{Mj} \end{bmatrix} \backsim \mathcal{N}\left(0, \begin{bmatrix} \sigma^2_{u_0} & \cdots & \cdots & \cdots & \sigma_{u_{0M}} \\ \vdots & \ddots & \vdots & & \vdots \\ \sigma_{u_{m0}} & \cdots & \sigma^2_{u_m} & \cdots & \sigma_{u_{mM}} \\ \vdots & & \vdots & \ddots & \vdots \\ \sigma_{u_{M0}} & \cdots & \cdots & \cdots & \sigma^2_{u_M} \end{bmatrix}\right) \tag{4.9}$$

$$\text{for } m = 1, ..., M \text{ and for } j = 1, ..., J$$

$$e_{ij} \backsim \mathcal{N}(0, \sigma_e^2) \text{ for } i = 1, ..., I \text{ and } j = 1, ..., J$$

Equation (4.6) is the regression equation at stimulus level. A_{ij} is the annoyance rating of the individual j for the stimulus i, π_{0j} is the intercept, π_{mj} is the regression slope for variable m ($m = 1, ..., M$) and e_{ij} is the residual error term. This last term is assumed to have a mean of zero and a variance of σ_e^2 to be estimated.

Equations (4.7) and (4.8) are regression equations at individual level. Noise sensitivity is introduced to explain the variation of the intercept and of the slopes; it does not vary across stimuli. Random u-terms u_{0j} and u_{mj} are residual errors terms at individual level. Residual terms are assumed to have a mean of zero, a variance of σ^2_{u0} and σ^2_{um}, respectively, to be estimated and are assumed to be independent from residual errors e_{ij} at stimulus level. The regression coefficients β_{00}, β_{01}, β_{m0} and β_{m1} are fixed parameters: they do not vary across individuals.

A step-by-step procedure is used in order to introduce relevant parameters into the equation. First, null models (without explanatory variables at stimulus level, with and without explanatory variables at individual level) are fitted. These models are used as a baseline for further model comparison. Then, noise index is inserted into a two-level model. Their slope can be either fixed or random.

Computations: The computation of multilevel regression is Bayesian and inference about studied parameters are made using their Bayesian posterior distribution [49]. Posterior distributions of model parameters are approximated via Markov Chain Monte Carlo (MCMC) simulation, with 290,000 iterations. This simulation is performed using the multilevel model fitting software MLwiN, v2.31.

Model selection: In order to select the model which enables a better calculation of annoyance ratings, three criteria are used:

- R_1^2: the proportion of variance explained at stimulus level. R_1^2 varies from 0 to 1. The closer R_1^2 is to 1, the better is the goodness-of-fit of the model to the data.
- $R_{2,m}^2$ (m=0, ..., M): the proportion of variance explained at individual level. This criterion is computed for each random coefficient at stimulus level: the intercept π_{0j} and the slopes π_{mj}. This criterion enables us to evaluate if noise sensitivity explains variation of each random coefficient (π_{0j} or π_{mj}). $R_{2,m}^2$ varies from 0 to 1. The closer $R_{2,0}^2$ (calculated for π_{0j}) is to 1, the more noise sensitivity has an effect on individuals' mean rating. The closer $R_{2,m}^2$ (calculated for π_{mj}) is to 1, the more noise sensitivity has a moderating effect on the relationship between the m^{th} index and annoyance ratings.
- Deviation Information Criterion (DIC): This criterion provides a measure of out-of-sample predictive error [49]. The lower the DIC is, the better is the predictive power of the model. When comparing two models, differences in DIC, of more than 10, might rule out the model with the higher DIC; differences between 5 and 10 are substantial; for a DIC difference less than 5, it could be misleading to report the model with the lower DIC [127].

Application to the experimental data set: First, two null models are tested: one without noise sensitivity at individual level (M0a) and one with noise sensitivity at individual level (M0b) (*cf.* Table 4.4).

For model M0b, $R_{2,0}^2$ reaches 0.26 and β_{01} is significantly different from 0. Thus, noise sensitivity has an effect on the intercept π_{0j}, and hence on participants' mean annoyance ratings: participants with high noise sensitivity give high annoyance ratings. Therefore noise sensitivity is kept for intercept modeling and M0b is further used as a baseline.

Two-level regression models are built with one single index as a stimulus-level explanatory variable. First, loudness N is considered as single index at stimulus level [4]. Three types of single-index model are studied: model M1 with π_{1j} as fixed slope, only equal to β_{10} (see Equation (8)), model M2 with π_{1j} considered as random slope, equal to $\beta_{10} + u_{1j}$ (see Equation (8)), and model M3 with π_{1j} as a random slope using noise sensitivity (see Equation (8)) in order to test the moderating effect of noise sensitivity on the relationship

4. When studying two-level model using L_{Aeq} without noise sensitivity and without an individual error term in the intercept, as done by Miedema and Oudshoorn [82], R_1^2 is equal to 0.12, which is the part of the variance at stimulus level explained by L_{Aeq}.

Table 4.4: Null models M0a and M0b, respectively without and with noise sensitivity as individual-level explanatory variable. Coef. (95% CI): Coefficient and its 95% Bayesian credibility interval; 1^{st} Level: Stimulus Level; 2^{nd} Level: Individual Level.

Null model	M0a without noise sensitivity	M0b with noise sensitivity
	Coef. (95% CI)	Coef. (95% CI)
Fixed part		
β_{00} (Intercept)	4.37 (3.72; 5.00)	1.93 (0.42; 3.41)
β_{01} (*Sens*)	–	0.43 (0.18; 0.68)
Random part		
σ_e^2 (1^{st} Level)	2.09 (1.90; 2.29)	2.09 (1.90; 2.29)
σ_{u0}^2 (2^{nd} Level)	3.47 (2.09; 5.67)	2.56 (1.53; 4.25)
Explained variance		
R_1^2 (1^{st} Level)	0.60	0.60
$R_{2,0}^2$ (2^{nd} Level)	–	0.26
DIC	3314.2	3313.8

between noise annoyance and loudness. The results are shown in Table 4.5. The index at stimulus level is grand-mean centered.

Both models M1 and M2 outperform the null model M0b (*cf.* Table 4.4): DIC is decreased by more than 300. Furthermore, rendering the slope random improves the goodness-of-fit of the model (R_1^2 is increased by 2%) and the out-of-sample predictive error (DIC is decreased by 73). For model M3, the cross-level interaction coefficient β_{11} between loudness and noise sensitivity is not significantly different from zero. Thus, noise sensitivity does not appear to have a moderating effect on the relationship between loudness and noise annoyance. Despite the value of $R_{2,1}^2$, noise sensitivity is not conserved for further modeling of the slope π_{1j}. Comparable results are found for single-index models using other indices displayed in Tables II and III, such as URA instead of N.

In order to improve annoyance modeling, we use indices which allow the characterization of different influential acoustical features mentioned by participants (*cf.* Section 2.1). According to previous results (*cf.* Section 2.2), several combinations of indices are tested through multilevel regression analysis. The selection of noise indices to be used in models is governed by participants' verbalizations. First, indices to characterize noise intensity and temporal amplitude variation are introduced in models, followed by indices characterizing spectral content and finally, indices to characterize modulation-related sensations. The three best combinations are kept, according to DIC and $R_{2,1}^2$ criteria: i) N and $\sigma'(N)$ (model LD, for "Loudness and its Derivative"), ii) N, $\sigma'(N)$ and $TETC$ (model $LDTC$, for "Loudness, its Derivative and Tonal Components") and iii) URA and $\sigma'(N)$ (model $URAD$, for "Urban Road vehicle pass-by noise Annoyance and loudness Derivative"). Some other combinations of indices in agreement with participants' verbalizations (*e.g.* N, $\sigma'(N)$ and S or other modulation indices) were not kept for annoyance modeling, according to partial correlation analysis. Standardized coefficients are calculated using the z-scores of all variables, in order to compare the contribution of each index to the models.

All regression coefficients are significantly different from 0. Comparing DIC value with previous models, models LD and $URAD$ are significantly improved when considering temporal derivative of loudness $\sigma'(N)$, *i.e.* the out-of-sample predictive error (DIC) is significantly decreased. Concerning $LDTC$ compared with LD, DIC value is decreased by 7:

Table 4.5: Multilevel models involving loudness with a fixed slope, with a random slope and with a moderating effect. The values of N are grand mean centred with the grand-mean 7.22 sones computed across the 27 stimuli. Coef. (95% CI): Coefficient and its 95% Bayesian credibility interval; 1^{st} Level: Stimulus Level; 2^{nd} Level: Individual Level. The covariances between residual errors at the individual level are not shown.

Model:	M1	M2	M3
Index:	N	N	N
Slope:	fixed slope	random slope	moderating effect
	Coef. (95% CI)	Coef. (95% CI)	Coef. (95% CI)
Fixed part			
β_{00} (Intercept)	1.91 (0.38; 3.42)	2.02 (0.49; 3.61)	1.91 (0.37; 3.44)
β_{01} (*Sens*)	0.43 (0.19; 0.68)	0.41 (0.15; 0.66)	0.43 (0.18; 0.69)
β_{10} (*Index*)	0.54 (0.49; 0.59)	0.54 (0.44; 0.64)	0.31 (0.05; 0.58)
β_{11} (*Index* × *Sens*)	–	–	0.04 (-0.004; 0.08)
Random part			
σ_e^2 (1^{st} Level)	1.39 (1.27; 1.53)	1.25 (1.14; 1.37)	1.25 (1.14; 1.37)
σ_{u0}^2 (2^{nd} Level)	2.59 (1.56; 4.27)	2.67 (1.61; 4.40)	2.66 (1.61; 4.36)
σ_{u1}^2 (2^{nd} Level)	–	0.07 (0.03; 0.12)	0.06 (0.03; 0.11)
Explained variance			
R_1^2 (1^{st} Level)	0.74	0.76	0.76
$R_{2,0}^2$ (2^{nd} Level)	0.26	0.26	0.26
$R_{2,1}^2$ (2^{nd} Level)	–	0	0.11
DIC	2942	2869	2869

the difference is not significant and the proportion of explained variance is not significantly increased. It is not possible to decide whether the model $LDTC$ is better than LD.

Using standardized coefficients, the contribution of each variable to the model can be determined [5]. Noise sensitivity highly contributes to the three models (51% for LD, 54% for $LDTC$ and 53% for $URAD$). This highlights the importance to consider explanatory variables at individual level in annoyance models. Moreover, the contribution of noise indices to the models are different. Thus, acoustical features do not equally contribute to annoyance. In model LD, the contribution of the temporal derivative of loudness seems to be slightly higher than the one of mean loudness (26% versus 23%). On the other hand, in model $URAD$, the contribution of the temporal derivative of loudness seems to be slightly lower than the one of URA which accounts for noise intensity, spectral content and modulation-related sensation [61] (23% versus 24%). In the model $LDTC$, loudness and its temporal derivative seem to equally contribute to the model (20%) and $TETC$ accounting for spectral content contributes less to the model (6%). Thus, the contributions of indices to the models reflect the participants' verbalizations: they mention perceived noise intensity as often as temporal amplitude variation, and these acoustical features are much more frequently mentioned than spectral content or than modulation-related sensations. It could also be noted that, in a model with loudness and its temporal derivative, this latter index seems to contribute a little bit more to the model than loudness. If more indices are

5. The contibution of each variable to the model is calculated by dividing the corresponding standardized coefficient by the sum of all standardized coefficients. For example, to estimate the contribution of noise sensitivity to the model LD, the standardized coefficient β_{01} (0.40) is divided by the sum of the standardized coefficients β_{01}, β_{10} and β_{20} ($0.40 + 0.20 + 0.18 = 0.78$), *i.e.* the contribution of noise sensitivity to the model LD is equal to 51%.

Table 4.6: Multilevel models involving multiple indices with random slopes. The values of N, $\sigma'(N)$, $TETC$ and URA are grand-mean centred with the respective grand mean 7.22 sones, 40.88 sone/s, 72.18 dB and 5.45 computed across the 27 stimuli. Coef. (95% CI): Coefficient and its 95% Bayesian credibility interval; [*St. Coef. (95% CI)*]: Standardized Coefficient and its 95% Bayesian credibility interval; 1^{st} Level: Stimulus Level; 2^{nd} Level: Individual Level. The covariances between residual errors at the individual level are not shown.

Model:	*LD*	*LDTC*	*URAD*
Index:	N & $\sigma'(N)$	N, $\sigma'(N)$ & $TETC$	URA & $\sigma'(N)$
	Coef. (95% CI) [*St. Coef. (95% CI)*]	Coef. (95% CI) [*St. Coef. (95% CI)*]	Coef. (95% CI) [*St. Coef. (95% CI)*]
Fixed part			
β_{00} (Intercept)	2.05 (0.39; 3.64)	1.69 (0.08; 3.27)	1.98 (0.30; 3.60)
β_{01} ($Sens$)	0.41 (0.14; 0.68)	0.47 (0.21; 0.73)	0.42 (0.15; 0.70)
	[*0.40 (0.14; 0.66)*]	[*0.45 (0.21; 0.70)*]	[*0.41 (0.14; 0.68)*]
β_{10} ($Index$ 1: N or URA)	0.27 (0.07; 0.46)	0.26 (0.06; 0.46)	0.52 (0.17; 0.87)
	[*0.18 (0.05; 0.30)*]	[*0.17 (0.04; 0.31)*]	[*0.19 (0.06; 0.32)*]
β_{20} ($Index$ 2: $\sigma'(N)$)	0.07 (0.03; 0.10)	0.06 (0.01; 0.10)	0.06 (0.02; 0.10)
	[*0.20 (0.08; 0.31)*]	[*0.17 (0.04; 0.30)*]	[*0.18 (0.06; 0.30)*]
β_{30} ($Index$ 3: $TETC$)	–	0.04 (0.003; 0.08)	–
	–	[*0.05 (0.004; 0.09)*]	–
Random part			
σ_e^2 (1^{st} Level)	1.19 (1.08; 1.31)	1.17 (1.06; 1.29)	1.19 (1.08; 1.31)
	[*0.23 (0.21; 0.25)*]	[*0.22 (0.20; 0.25)*]	[*0.23 (0.21; 0.25)*]
σ_{u0}^2 (2^{nd} Level)	2.75 (1.65; 4.48)	2.82 (1.72; 4.65)	2.75 (1.65; 4.51)
	[*0.52 (0.31; 0.85)*]	[*0.54 (0.33; 0.89)*]	[*0.52 (0.32; 0.86)*]
σ_{u1}^2 (2^{nd} Level)	0.19 (0.08; 0.38)	0.20 (0.09; 0.40)	0.56 (0.21; 1.15)
	[*0.08 (0.03; 0.17)*]	[*0.09 (0.04; 0.17)*]	[*0.08 (0.03; 0.16)*]
σ_{u2}^2 (2^{nd} Level)	0.006 (0.002; 0.014)	0.01 (0.003; 0.02)	0.01 (0.00; 0.02)
	[*0.06 (0.02; 0.13)*]	[*0.07 (0.03; 0.14)*]	[*0.06 (0.02; 0.13)*]
σ_{u3}^2 (2^{nd} Level)	–	0.003 (0.001; 0.006)	–
	–	[*0.004 (0.001; 0.009)*]	–
Explained variance			
R_1^2 (1^{st} Level)	0.77	0.78	0.77
$R_{2,0}^2$ (2^{nd} Level)	0.25	0.25	0.25
DIC	2841	2834	2842

involved in the model, the contribution of temporal derivative of loudness decreases in favor of these additional indices.

3 Discussion

Noise annoyance is assessed under controlled conditions in the laboratory to study the effect of different compositions of urban road traffic comprising buses, PTWs, heavy and light vehicles. The main objectives are: i) to identify acoustical features influencing noise annoyance, ii) to characterize them using indices and iii) to take them into account in annoyance models as a contribution to enhance current annoyance models. Concerning annoyance due to noise from urban road vehicles, contributions to enhance annoyance model have been made: i) for urban road vehicle pass-by noises (per perceptual category [91] or regardless of the perceptual category [61]) and ii) for highway noise [112, 139]. For models considering road traffic, the specific part of PTWs within the traffic is not separately given as they are aggregated with light vehicles. However, several studies demonstrated that PTWs are more annoying than the other types of vehicles (*e.g.* [103]). Furthermore, the noise of these vehicles possesses specific acoustical features which should be considered in an annoyance model [103, 137]. The verbalization task performed by participants at the end of the experiment confirms the necessity to carefully consider a specific class of vehicles: PTWs were denoted as annoying, notably because of their spectral features and their modulation-related sensations, as found by Paviotti and Vogiatzis [103]. Thus, taking into account PTWs as specific vehicle category in the traffic composition is of great importance to improve noise annoyance model. Moreover, the most often cited features for urban road traffic noise sequences are perceived noise intensity and temporal amplitude variations within the sequences. These acoustical features are known to influence annoyance ratings (*e.g.* [77, 103]) and should also be implemented in annoyance model.

A correlation analysis shows that noise intensity-related indices (N and L_{Aeq}) and URA indicator (calculated using N, in particular) are highly correlated with annoyance. On the other hand, TNI only shows a low correlation coefficient with annoyance, despite the fact that this index was developed to characterize long term exposure to road traffic noise. Regarding the actual study, the results can be explained by the smaller variation in L_{10} than in L_{90} between the tested noise sequences. For 3-minute noise sequence of highway noise, Yaniv *et al.* [139] also found that TNI is the worst predictor of annoyance.

In order to assess the quality of annoyance models for urban road traffic noise with explanatory variables at stimulus and individual levels, multilevel linear regressions are performed:

- Three combinations of noise indices as explanatory variables at stimulus level are investigated: i) mean loudness and its temporal derivative, ii) mean loudness, its temporal derivative and the total energy of specific tonal components and iii) the URA indicator developed by Klein *et al.* [61] (using N, m_{sputt}, m_{nasal} and $TETC$) and the temporal derivative of loudness.
- Noise sensitivity is introduced into the annoyance models as an explanatory variable at individual level.

Three combinations of indices lead to comparable goodness-of-fit of the models (R_1^2) and out-of-sample predictive errors (DIC). An increase in annoyance is linked to an increase in loudness, in its temporal derivative and in the energy of specific tonal components. The temporal derivative of loudness may arise from both traffic density and temporal amplitude variations within a pass-by noise (*e.g.* changing gears, quick or slow acceleration, etc.). The $TETC$ index characterizes high frequency content of urban transportation noises (*cf.* [61, 130, 131]). The models tested in the current study use indices which summarize acoustical features of urban road traffic noise mentioned by participants. Several studies [77, 61, 130, 103, 94, 139] mention these acoustical features as influential sensations in annoyance assessment. However, on the basis of the actual data, no substantial differences appear among the three models and hence, it is not possible to decide for an optimal one. In a next step, the models should be validated using *in situ* survey, comprising especially the measure of noise sensitivity.

Indeed, the contribution of noise sensitivity is found to be significant in the intercept equation (*cf.* Equation (4.7)), as found by Trollé *et al.* [130]. Noise sensitivity influences the mean annoyance rating, however, no moderating effect on the relationship between annoyance and noise indices is observed. The same result was found for tramway noise in the laboratory (*e.g.* [116, 130, 131]) and for *in situ* aircraft noise (*e.g.* [133]). However, several authors found a moderating effect for *in situ* road and aircraft noises (*e.g.* [84]) or for *in situ* road noise (*e.g.* [99]). This is in favor of taking into account noise sensitivity in annoyance models for further *in situ* studies. Furthermore, annoyance models highlighted in the current study show that noise sensitivity contributes more than 50% to the calculation of noise annoyance. So, half of the contributions to the model are due to individual factors and the rest to acoustical features. This tendency was demonstrated with *in situ* data by Taylor [125] who proposed a path model for aircraft noise annoyance. He found that noise sensitivity had the strongest effect on annoyance. In conclusion, in the current study considering different acoustical features and in field studies (*e.g.* [82, 125]), the models demonstrate that some non-acoustical factors may provide a considerable contribution to annoyance and hence they should be introduced into annoyance models. To validate such a model, noise sensitivity should be registered during *in situ* surveys, as was already done in former studies (*e.g.* [5, 125, 54, 84, 99]).

4 Conclusion

This study contributes to the long-term requirement to improve noise annoyance prediction, by proposing indicators based on noise sensitivity and on acoustical and psychoacoustical indices. These indices account for annoying acoustical factors of different compositions of urban road traffic comprising PTWs, buses, heavy and light vehicles. The analysis of the experimental data revealed the following findings:

- Participants note the presence of PTWs much more than the presence of other types of vehicle.
- Most of the participants explicitly associate PTWs to annoyance, notably because of their spectral features, their modulation-related sensations and their driving conditions.
- The most often cited acoustical features are perceived noise intensity and temporal amplitude variation of noise, followed by spectral content and modulation-related sensations.
- For annoyance modeling, a multilevel regression is performed in order to consider explanatory variables both at individual level and at stimulus level. Three tested

combinations of different noise indices appear promising for future studies: they allow consideration of several influential acoustical features mentioned by participants, in particular noise intensity and temporal amplitude variation. Spectral content and modulation-related sensations are also included in the combinations. For the characterization of temporal amplitude variation, a new index is proposed: the temporal derivative of loudness $\sigma'(N)$. This index highly contributes to the performance of the three models. In combination with loudness only, the contribution of $\sigma'(N)$ to the model seems to be slightly higher than that of loudness.

- Noise sensitivity is introduced as an explanatory variable at individual level. Noise sensitive participants give higher mean annoyance ratings, but no moderating effect on the relationship between annoyance and noise indices is found. The contribution of noise sensitivity to the model seems to be the highest compared to all explanatory variables. This highlights that such individual data have to be considered in further studies dealing with noise annoyance and noise annoyance modeling.
- The present experiment shows that the three annoyance models under investigation, using a relevant combination of noise indices coupled with noise sensitivity, are equally appropriate in terms of goodness-of-fit. Their respective predictive power has to be tested on the prediction of survey data, that is to say comparing noise annoyance predicted with the models to annoyance measured during the survey.

Résumé des principaux résultats

♣ Les participants ont relevé la présence de deux-roues motorisés bien plus souvent que celle des autres types de véhicules et les ont explicitement associés à la gêne sonore.
♣ Les caractéristiques acoustiques les plus citées sont l'intensité sonore perçue et les fluctuations d'amplitude, suivies par le contenu spectral et la présence de sensations liées aux modulations.
♣ Un nouvel indice, $\sigma'(N)$, la valeur efficace de la dérivée temporelle de la sonie, a été proposé pour caractériser les fluctuations d'amplitude.
♣ Une régression multi-niveau a été utilisée pour calculer la gêne à partir de la sensibilité au bruit et de combinaisons d'indices relatifs aux caractéristiques acoustiques les plus citées. Trois combinaisons d'indices se sont révélées pertinentes à l'issue des régressions multi-niveau menées.
♣ La sensibilité au bruit contribue fortement aux modèles de gêne, sans effet modérateur sur la relation entre la gêne et les indices acoustiques.
♣ L'indice $\sigma'(N)$ contribue significativement aux 3 modèles.

Et après ?

Ce chapitre a montré l'influence sur la gêne de 4 caractéristiques acoustiques du bruit de trafic routier urbain. Des combinaisons d'indices permettant de rendre compte de ces caractéristiques acoustiques ont été introduits dans des modèles de gêne, ainsi que la sensibilité au bruit, conformément aux résultats du Chapitre 2.

Les séquences sonores construites dans le cadre de ce chapitre vont être utilisées dans le Chapitre 6 afin d'étudier la gêne en situation de multi-exposition aux bruits de trafic routier urbain et d'avion. De plus, les résultats de ce chapitre serviront de base à l'analyse des données de gêne du Chapitre 6.

Avant d'étudier les situations de multi-exposition aux bruits de trafic routier urbain et d'avion au Chapitre 6, il s'agit de caractériser physiquement et perceptivement le bruit d'avion du point de vue de la gêne, en conditions contrôlées. Ce travail est mené au Chapitre 5.

Chapitre 5

Caractérisation physique et perceptive des bruits d'avion

Ce chapitre est composé d'un article accepté pour publication par Applied Acoustics. Cet article est intitulé ***"Aircraft noise annoyance modeling : consideration of noise sensitivity and of different annoying acoustical characteristics"****. Il est co-écrit avec Catherine Marquis-Favre et Reinhard Weber. La collaboration de Reinhard Weber a porté sur la recherche d'indices caractéristiques du bruit d'avion.*

Questions scientifiques

Les questions auxquelles nous souhaitons répondre dans ce chapitre sont les suivantes :

- ♣ Quels sont les facteurs acoustiques qui influencent la gêne due aux bruits de passage d'avion ?
- ♣ Quels indices permettent d'expliquer la gêne due aux bruits de passage d'avion ?
- ♣ La sensibilité des participants de l'expérience permet-elle d'expliquer une part de la variance des réponses de gêne de court-terme due aux bruits de passage d'avion ?

Une expérience avec mise en situation a été réalisée, au sein de laquelle les participants ont évalué la gêne due à des bruits d'avion. Ce chapitre utilise les résultats du Chapitre 2 pour améliorer les modèles de gêne en considérant à la fois des facteurs non-acoustique et acoustiques. De plus, l'indice $\sigma'(N)$ développé au Chapitre 4 a été utilisé pour caractériser les fluctuations d'amplitude des bruits d'avion.

Abstract

Noise annoyance due to aircraft flyover noise was assessed under laboratory conditions. The main objectives of the study were: i) to identify influential acoustical features of noise annoyance, ii) to propose noise indices to characterize these acoustical features and iii) to enhance annoyance models including influential acoustical and non-acoustical variables. Therefore, a verbalization task was performed by the participants of the experiment to collect their whole impression concerning the aircraft flyovers noises for which they rated annoyance. This verbalization task highlights that noise annoyance was influenced by three main acoustical features: i) the spectral content, ii) the temporal variation and iii)

the perceived sound intensity. Four combinations of noise indices were used to propose multilevel annoyance models, in combination with the individual noise sensitivity. Noise sensitivity was found to highly contribute to annoyance models and should therefore be considered in future studies dealing with noise annoyance due to aircraft noise. Different combinations of noise indices coupled with noise sensitivity were found to be promising for future studies that aim to enhance current annoyance models.

Introduction

In Europe, even if aircrafts have become less noisy over years, air traffic has increased [23]. Therefore, more people are exposed to aircraft noise. Until now, noise management is based on energy-based indices. For example, the European directive 2002/49/EC requires that European cities of more than 100,000 inhabitants produce strategic noise maps for several environmental noise sources, such as aircraft noise. These maps characterize noise exposure using the energy-based index L_{den} – the day-evening-night level.

This index was used by Miedema and Oudshoorn [82] to propose exposure-response relationships: they linked the day-evening-night level of a transportation noise to the percentage of people reporting a certain amount of noise annoyance. These relationships are therefore recommended by the European Commission and used by the World Health Organization to estimate the number of disability-adjusted life years (DALYs) due to noise annoyance [138]. However, different studies showed that these relationships did not allow a good prediction of noise annoyance measured during recent socio-acoustical surveys (*e.g.* [41]).

In addition, several studies demonstrated that such an energy-based index explains only a small part of the whole variance in noise annoyance (*e.g.* [57]). Indeed, noise annoyance is further influenced by numerous acoustical features (*e.g.* spectral distribution of energy [77]) as well as by non-acoustical factors (*e.g.* noise sensitivity [133]).

Concerning aircraft noise, different acoustical characteristics contribute to the whole impression of the noise (*cf.* Chapter 1, Section 2.2.3). For example, Barbot *et al.* [3] performed a preference test on aircraft noises to investigate dimensions of sound perceptual representation. Participants were asked to explain their preference. Three acoustical features of aircraft noise emerged within the descriptive adjectives given by the participants: i) the timbre aspect, divided into pitch, texture of noise and compound nature of noise, ii) the temporal aspect and iii) the intensity aspect.

Several indices have already been used in literature to characterize these acoustical features of transportation noises. For example, the timbre aspect has been characterized using sharpness (denoted as S) for aircraft noise [3], the roughness (denoted as R) for road vehicle noise [91], the total energy of tonal components in high critical bands (denoted as $TETC_{x-y}$) for tramway noise [130, 131] and road vehicle noise [61], *etc.* The temporal aspect has been characterized using a noise level derivative index (denoted as σ') for aircraft noise [94], the variance of time-varying A-weighted pressure normalized by RMS A-weighted pressure (denoted as VAP) for tramway pass-by noise [130, 131], the fluctuation strength (denoted as F) for aircraft noise [3], *etc.* Finally, the intensity aspect has been characterized using the A-weighted equivalent sound pressure level (denoted as L_{Aeq}) or the loudness (denoted as N) for road vehicle noise (*e.g.* [91]).

The aim of the present paper is to enhance annoyance modeling for aircraft flyover noise by considering noise sensitivity and acoustical features that influence noise annoyance. The study is carried out under laboratory conditions for different aircraft flyover noises. After identifying different influential acoustical features, different indices are tested in order to take these acoustical features into account. Then, multilevel regression is performed in order to consider noise sensitivity as an explanatory variable at individual level and relevant noise indices at stimulus level. Multilevel regression analysis allows to identify promising annoyance models. This paper is organized as follows: the listening experiment is described in Section 1, results are exposed in Section 2 and the discussion is given in Section 3.

1 Experimental methodology

The experiment aims to assess short-term annoyance due to aircraft flyover noise in laboratory conditions.

1.1 Stimuli

For the experiment, 12 aircraft flyover noises were recorded in the neighborhood of the international airport Orly (approximately 5 km away in line with the runway), near Paris, France. Aircraft height is less than 1,000 m, after take-off. The noises were recorded *in situ* using the ORTF technique in accordance with French standards. The ORTF couple was placed at a height of 1.5 m and at least at 2 m from any reflecting wall. This recording technique used for stereophonic sound reproduction in laboratory was used in previous studies dealing with moving sources (e.g. [130, 131]) as it is known for its good representation, readability, plausibility and overall reproduction quality for fixed and moving noise sources [45].

The A-weighted equivalent sound pressure level (denoted as L_{Aeq} [1]) of the aircraft flyover noises was measured using a B&K 2250 sonometer. Differences in L_{Aeq} observed *in situ* were kept, resulting in a range from 43.5 dB(A) to 54.6 dB(A). Table 5.1 gives for each aircraft flyover noise: stimulus duration, 10 dB-down duration (duration of the aircraft noise event during which the noise level lies not more than 10 dB(A) below the highest noise level, *e.g.* [94]), A-weighted equivalent sound pressure level L_{Aeq}, single event noise exposure level (denoted as L_{AE}) and A-weighted maximum sound pressure level (denoted as L_{Amax}).

The duration of the tested stimuli was imposed by the original duration of single aircraft flyover noises recorded *in situ*: in order to present aircraft noise in the same way as it is perceived by inhabitants, a stimulus lasted as long as the aircraft flyover noise was perceptually discernible from the background noise. Durations varied between 22.1 s and 61.5 s. The 10 dB-down duration was also given as this index is often used to describe aircraft noise (*e.g.* [94]). Previous studies demonstrated that stimulus duration has a limited or no influence on short-term noise annoyance. Paulsen [101] showed that stimulus duration of highway road traffic noises ranging from 1 to 80 s had a very limited influence on annoyance judgments. For single urban road traffic pass-by noises, Morel *et al.* [91] and

1. L_{Aeq} is calculated over the duration of the noise sequence.

Klein *et al.* [61] found that stimulus duration between 3 and 9 s was not a criterion to formulate annoyance judgments. The same conclusion was drawn by Trollé *et al.* [130, 131] for single tramway pass-by noises with durations ranging from 8 to 25.5 s.

Table 5.1: Duration, 10 dB-down duration, L_{Aeq} [1], L_{AE} and L_{Amax} of 12 aircraft flyover noises. L_{Aeq}: A-weighted energy equivalent sound pressure level, L_{AE}: single event noise exposure level and L_{Amax}: A-weighted maximum sound pressure level.

stimulus	duration (s)	10 dB-down duration (s)	L_{Aeq} (dB(A))	L_{AE} (dB(A))	L_{Amax} (dB(A))
a1	54.9	20.1	49.4	67.3	58.2
a2	22.1	14.2	43.9	57.1	50.6
a3	35.9	13.6	52.8	68.8	61.6
a4	39.1	18.3	50.5	66.7	58.8
a5	48.0	12.6	52.8	70.0	62.4
a6	40.1	9.2	54.6	71.2	65.4
a7	44.3	9.5	51.9	69.2	63.7
a8	43.9	19.9	51.7	68.6	59.3
a9	42.5	17.8	52.0	68.9	60.8
a10	34.4	13.4	50.0	64.6	57.4
a11	61.5	12.1	43.5	60.7	53.5
a12	43.9	19.9	46.2	63.1	53.8

No filter simulating facade transmission was applied to the stimuli as wall material and window types have an effect on auditory judgments [128] and the choice of one specific kind of facade might have been too limiting. Thus, the worst noise exposure is considered (*e.g.* [2]) such as being in private outdoor spaces.

1.2 Apparatus

The listening experiment [2] took place in a quiet room with a background noise below 20 dB(A). Stimuli were reproduced employing a 2.1 audio reproduction system consisting of two active loudspeakers (Dynaudio Acoustics BM5A) and one active subwoofer (Dynaudio Acoustics BM9S).

Concerning positioning of participant and loudspeakers, the center of the interaural axis of the participant and the loudspeakers formed an equilateral triangle. This was in accordance with recommendations given by Bech and Zacharov [7]. The loudspeakers were placed at a height of 1.20 m from the floor, and the subwoofer was placed on the floor between the loudspeakers. The user interface was programed using MATLAB©.

An omnidirectrional microphone (GRAS 40AE) was placed at the participant's position in order to record the noise sequences. From the sequence recordings, acoustic and psychoacoustic indices were calculated using MATLAB© and dBSonic software (ACOEM) [?].

2. This experiment and the main experiment II presented in Chapter 3, Section 4 were carried out in two different sessions of a same test. The study of the potential effect of the order of each session within the test is presented in Appendix A, Section 2.

1.3 Procedure

Participants were asked to imagine themselves at home while relaxing (*e.g.* reading, watching television, discussing, gardening or doing other common relaxing activities). This procedure has been used in previous works (*e.g.* [59]). Prior to each experiment, the participants were trained. During the training and experiment, the stimuli were presented one by one in random order.

After each stimulus, a reminder of the imaginary situation was presented to the participants and they were asked: "*During your relaxing activity, you hear this noise. Does this noise annoy you?*" ("*Pendant votre activité relaxante, vous entendez cette séquence sonore. Cette séquence sonore vous gênerait-elle?*"). Participants gave ratings on a continuous scale ranging from "0" to "10", with 11 evenly spaced numerical labels and two verbal labels at both ends ("*not at all*" ("*Pas du tout*") and "*extremely*" ("*Extrêmement*")).

At the end of the experiment, the participants performed a verbalization task [3]: they answered two questions: "*Can you tell what you thought about the aircraft* noises?" ("*Pouvez-vous dire ce que vous avez pensé des bruits d'avion?*") and "*If you have found some noise sequences annoying, can you tell us why you found them annoying?*" ("*Si vous avez trouvé des séquences sonores gênantes, pouvez-vous nous dire pourquoi vous les avez trouvées gênantes?*"). If the first answer was very short, the experimenter asked three supplementary questions after the first one, in order to obtain more descriptions from the participant: "*Did the aircraft noise seem to be familiar to you?*" ("*Est-ce que le bruit des avions vous a paru familier?*"), "*Can you describe the aircraft noise?*" ("*Pouvez-vous décrire le bruit des avions?*") and "*In a general way, how do you judge aircraft noise?*" ("*De manière générale, comment jugez-vous le bruit des avions?*"). Then, they filled in a questionnaire with personal items such as non-acoustical factors. For noise sensitivity, participants were asked: "*Would you say you are sensitive to noise in a general way?*" ("*Diriez-vous que vous êtes sensible au bruit en général?*") and they had to make a judgment on a continuous scale ranging from "0" to "10" with two verbal labels at both ends ("*not at all sensitive*" ("*Pas du tout sensible*") and "*extremely sensitive*" ("*Extrêmement sensible*")), a similar scale to the one used to measure noise annoyance. Such one item scale was usually used to measure noise sensitivity in literature dealing with noise annoyance assessment (*e.g.* [84]). The experiment was usually lasting for thirty minutes.

1.4 Participants

The test was performed by 33 participants (19 male, 14 female) aged between 20 and 56 years old (mean age = 32; standard deviation = 12.5). All participants declared normal hearing abilities and were paid for their participation. 73 % of the participants declared no difficulty to perform the test.

2 Results

In this section, the results of the experiment will be presented, with the focus to enhance noise annoyance modeling.

3. The questionnaire is given in Appendix A, Section 1.

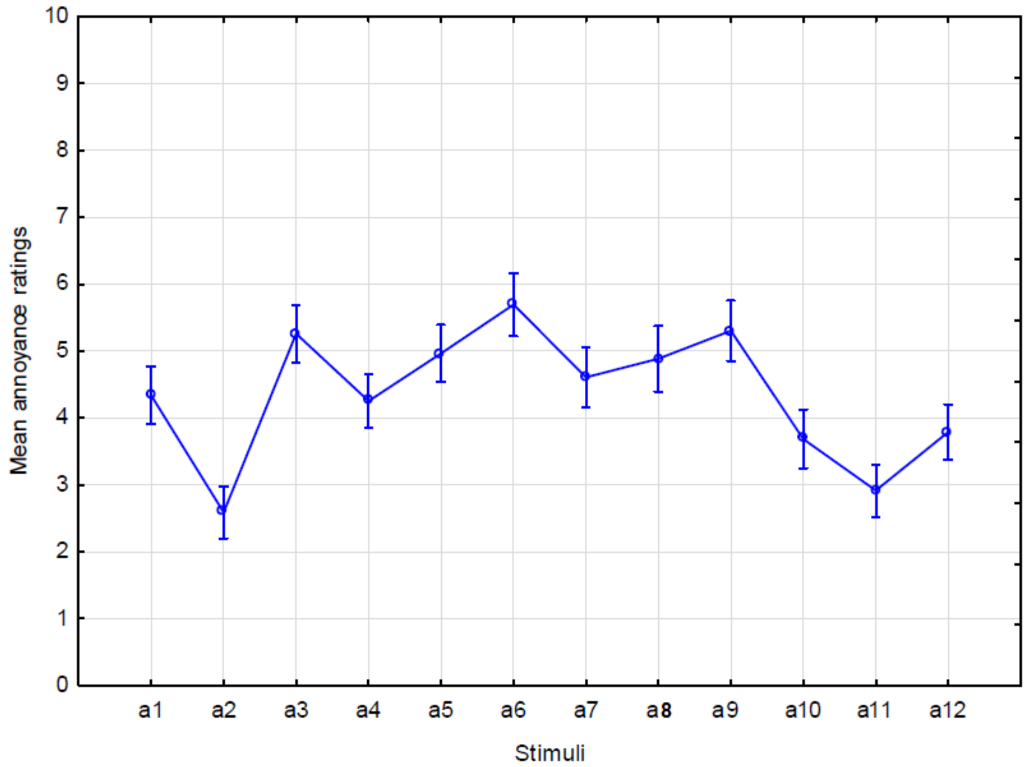

Figure 5.1: Mean annoyance rating for all aircraft flyover noise sequences. Vertical error-bars represent standard errors.

As can be seen in Figure 5.1, flyover noise sequences led to significant differences in annoyance ratings. A repeated measures ANOVA carried out on the annoyance ratings showed a significant effect of the factor "STIMULUS" [$F(11, 352) = 22.96$; $p<0.01$, $\epsilon=0.66$]. This factor explained 42% of the observed variance.

First, it should be noticed that the duration of the stimuli did not influence annoyance ratings. Indeed, a2 and a11 were two of the least annoying aircraft noises. They were respectively the shortest and the longest stimuli. This result was confirmed by a non-significant Bravais-Pearson correlation coefficient between annoyance and duration ($r=0.08$; $p=0.79$). The 10 dB-down duration was not significantly correlated with annoyance ($r=-0.08$; $p=0.81$), too.

2.1 Description of verbalizations

Among the 33 participants of the test, 19 mentioned the spectral content of aircraft noise. Most of them (17 out of 19 participants) described high frequency content (*"sharp"* (*"aigü"*), 13 occurrences, *"shrill"* (*"strident"*), 4 occ. and *"hissing"* (*"sifflement"*), 2 occ.). Low frequency content was less often mentioned (12 out of 19 participants) (*"deep"* (*"grave"*), 4 occ., *"dull"* (*"sourd"*), 8 occ.).

Eighteen participants mentioned global temporal variation of aircraft noise. Half of them described aircraft movement (*e.g. "approach"* (*"se rapproche"*), 3 occ. *"leave"* (*"partir"*), 3 occ.), half of them described noise fluctuation (*e.g. "quiet period followed by a very sharp*

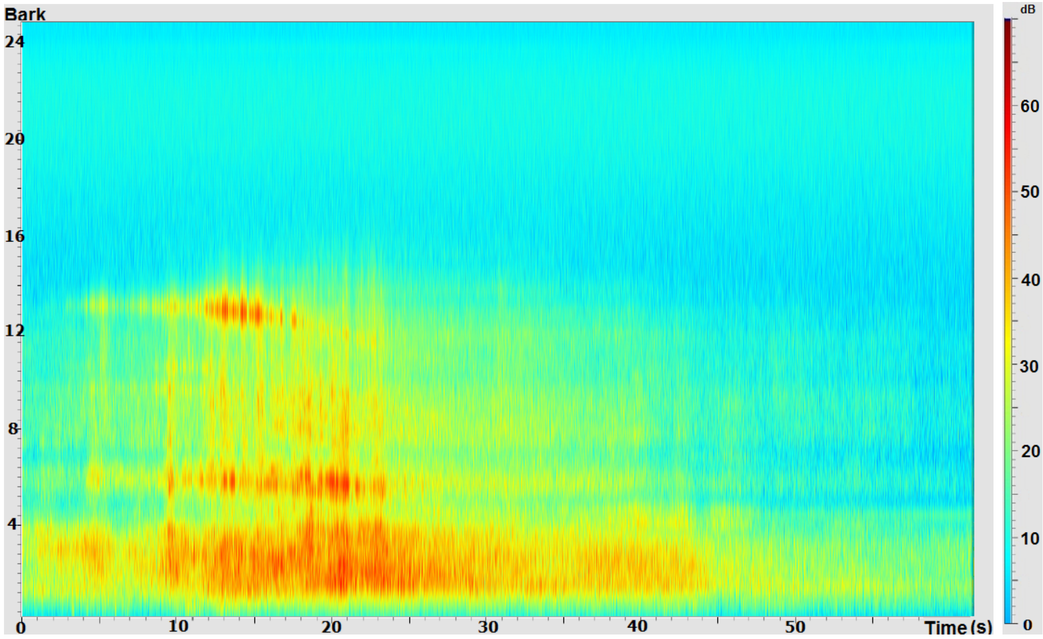

Figure 5.2: Auditory spectrogram of a11, one of the least annoying aircraft noises in the experiment.

period" (*"Moment calme puis moment très aigü"*)).

Thirteen out of all 33 participants mentioned also perceived sound intensity (*"loud"* (*"fort"*), 9 occ., *"noisy"* (*"bruyant"*), 2 occ. and *"intense/ intensity"* (*"intense/ intensité"*), 2 occ.). It seems therefore that spectral content influenced more the perception of aircraft noise than perceived sound intensity.

2.2 Analysis of the aircraft signals

As participants often mentioned the spectral content of aircraft noise, auditory spectrograms will be considered to determine relevant indices to account for main spectral features (*cf.* Figures 5.2, 5.3 and 5.4).

All aircraft flyover noises presented a high energy content at low and medium frequencies, within critical bands from 1 to 12 Barks, during their whole duration. This content is more important for the more annoying noises than for the less annoying ones. This part of the spectral content seemed to be linked to some verbalizations given by the participants such as the adjectives *"deep"* or *"dull"*. Furthermore, it seems that at high frequencies, within critical bands from 13 to 18 Barks, some tonal components were present with time-varying frequency during flyover. This time-variation is due to the Doppler effect of the moving source. These tonal components seemed to be related to some verbalizations mentioned by the participants such as *"hissing"*.

Furthermore, as the participants mentioned perceived sound intensity and global temporal variation of aircraft noise too, noise level as a function of time will be considered, for a2 and a6, on Figure 5.5.

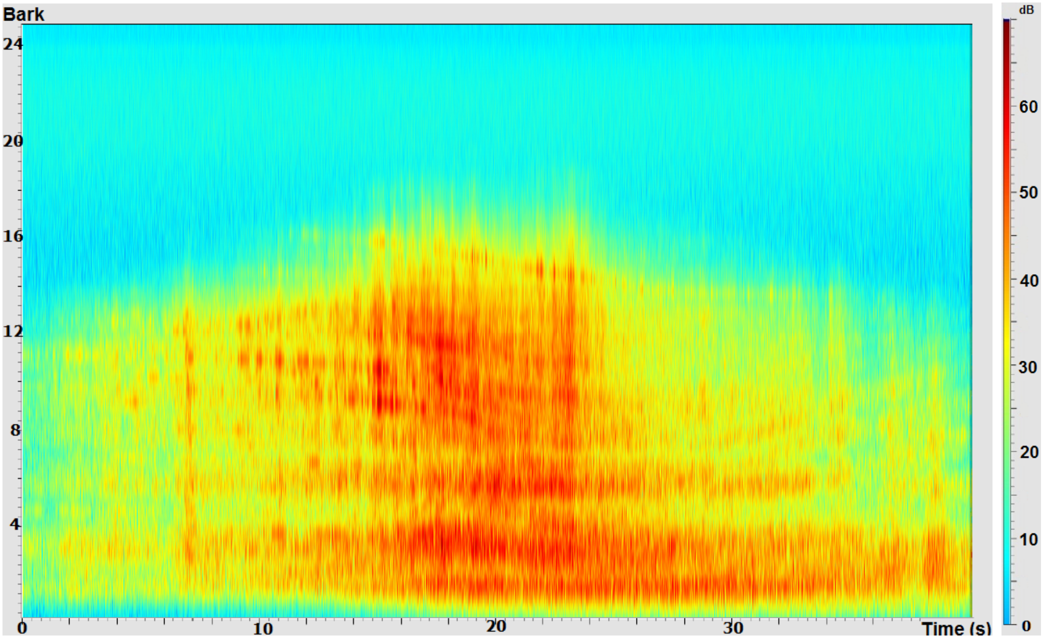

Figure 5.3: Auditory spectrogram of a6, one of the most annoying aircraft noise in the experiment.

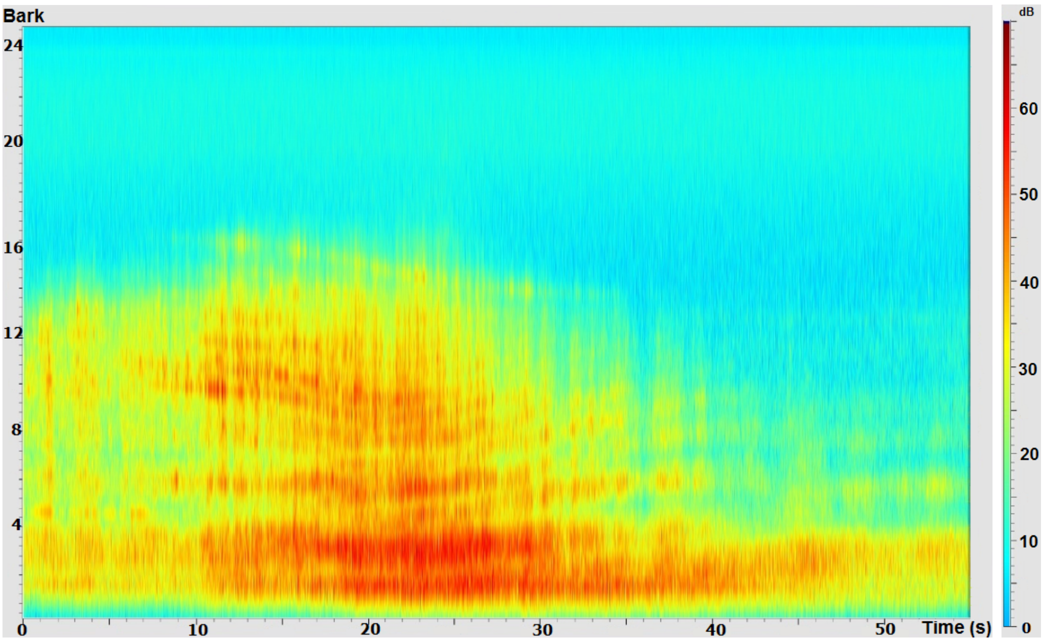

Figure 5.4: Auditory spectrogram of a1, significantly different from a11 and a6 in terms of annoyance rating (*cf.* Figure 5.1).

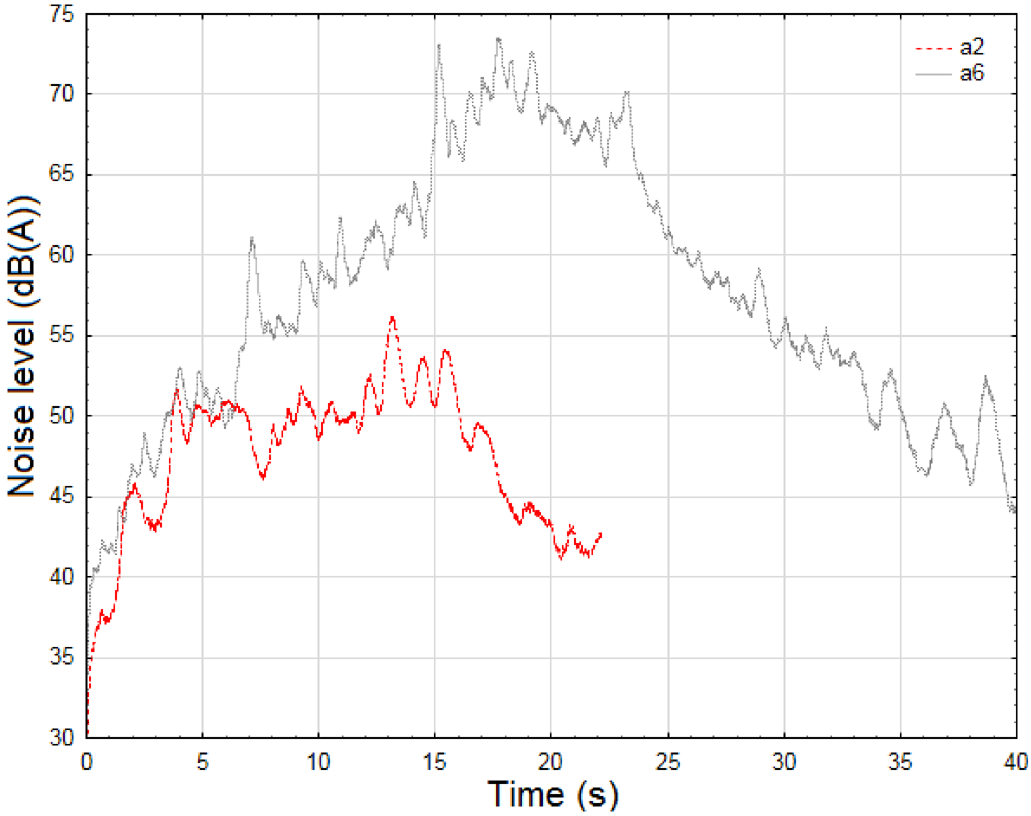

Figure 5.5: Noise level as a function of time for a2, one of the least annoying aircraft flyover noises, and a6 one of the most annoying ones (*cf.* Figure 5.1).

Noise level increases when aircraft flies towards the microphone and conversely, decreases when it flies away from it. Irregular amplitude variations happen during noise level increase and decrease. Global temporal variation and these irregular amplitude variations are more important and more numerous for a6, one of the most annoying aircraft noises, than for a2, one of the least annoying ones.

2.3 Proposition of relevant indices

To explain observed differences and to investigate the relationship between selected noise indices and mean annoyance ratings, Bravais-Pearson correlation coefficients r were calculated. These correlations may help in the interpretation of the acoustical features mentioned by participants (*cf.* Section 2.1). Correlations between annoyance ratings and different indices used in literature to characterize these acoustical features were computed [4]. Main indices are presented in Table 5.2: A-weighted equivalent sound pressure level (denoted as L_{Aeq}), single event noise exposure level (denoted as L_{AE}), A-weighted maximum sound exposure level (denoted as L_{Amax}), total loudness calculated every 2 ms and exceeded 10% of the time (denoted as N_{10}), mean specific loudness integrated between Barks 1 and 12 (denoted as N_{1-12} and proposed to characterize the energy in low and medium frequencies), mean sharpness (denoted as S), total energy of tonal components (*cf.* [130, 131], sum of the maximal (across time) level of tonal components in critical bands) within critical bands from 13 to 18 Barks (denoted as $TETC_{13-18}$ and used to characterize tonal components in high frequencies), temporal derivative of sound pressure level (denoted as σ', *cf.* [94]), temporal derivative of loudness (denoted as $\sigma'(N)$, *cf.* [43]), variance of A-weighted pressure (denoted as VAP, *cf.* [130, 131]), mean roughness (denoted as R, computed using the Aures' model, *cf.* [34?]) and mean fluctuation strength (denoted as F, *cf.* [34?]).

Table 5.2: Bravais-Pearson correlation coefficient r between noise annoyance ratings and indices: L_{Aeq}: A-weighted energy equivalent sound pressure level, L_{AE}: single event noise exposure level, L_{Amax}:A-weighted maximum sound pressure level, N_{10}: total loudness exceeded 10% of the time, N_{1-12}: mean specific loudness integrated between Barks 1 and 12, S: sharpness, $TETC_{13-18}$: total energy of tonal components within critical bands from 13 to 18 Barks, σ': temporal derivative of sound pressure level, $\sigma'(N)$: temporal derivative of loudness, VAP: variance of A-weighted sound pressure, R: mean roughness, F: mean fluctuation strength. (^{a}: p<0.001, ^{b}: p<0.01, ^{c}: p<0.05)

	L_{Aeq}	L_{AE}	L_{Amax}	N_{10}	N_{1-12}	S
r	0.96^a	0.96^a	0.91^a	0.98^a	0.88^a	0.30
	$TETC_{13-18}$	σ'	$\sigma'(N)$	VAP	R	F
r	0.86^a	-0.28	0.98^a	0.90^a	0.96^a	0.66^c

4. All the tested indices were not presented. Indeed, for some indices (*e.g.* the index L_{NP} highlighted in literature to be correlated with noise annoyance, *cf.* Chapter 1, Sections 2.2.3 and 2.3.5.2), other indices characterizing the same acoustical feature were better correlated with annoyance. For some other indices, they were not significantly correlated with annoyance such as the Tone-to-Noise Ratio. Finally, for some indices, their correlation with annoyance was due to the correlation between related indices and annoyance. For example, the index L'_{eq} (highlighted in literature to be correlated with noise annoyance, *cf.* Chapter 1, Sections 2.2.3 and 2.3.5.3) was significantly correlated with annoyance, but not displayed in Table 5.2 as the index σ' it is based on was not significantly correlated with annoyance. The correlation between L'_{eq} and annoyance is due to the high correlation of noise level with annoyance.

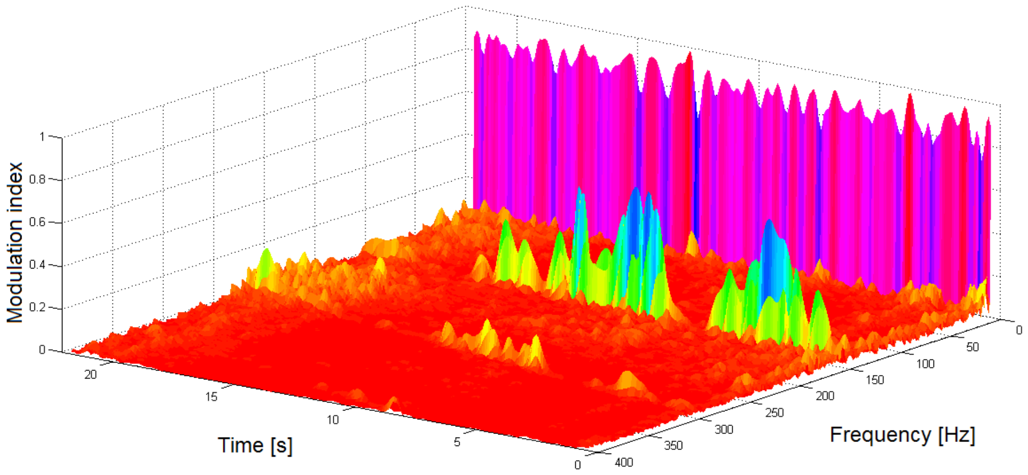

Figure 5.6: Modulation index spectrogram of a2, one of the least annoying aircraft noises of the experiment.

First, it should be noticed that energy-based indices L_{Aeq} and L_{AE} are highly correlated with annoyance. As L_{AE} is calculated from L_{Aeq} and noise duration (which is not correlated with annoyance), the correlation of L_{AE} with annoyance is explained by the correlation of L_{Aeq} with annoyance. Therefore, this index will not be used for modelling. Furthermore, N_{10}, which characterizes the loudest instantaneous perceived intensity during flyovers, and L_{Amax}, the highest sound pressure level, are highly correlated with annoyance. However, N_{10} correlates higher with annoyance compared to L_{Amax}. As both indices characterize similar acoustical features, only N_{10} will be considered in the following. N_{1-12}, which characterizes the perceived intensity at low and medium frequencies, is also highly correlated with annoyance. Astonishingly, sharpness S is not correlated with annoyance, although the participants used the word *"sharp"* to describe the aircraft flyover noises, whereas $TETC_{13-18}$ is correlated with annoyance. Considering indices accounting for periodic temporal variability of the noises, R and F are correlated with annoyance. Regarding indices that account for irregular amplitude variations of the noises, σ' is not correlated with annoyance, in contrast to VAP and $\sigma'(N)$.

In order to propose annoyance models accounting for several annoying sound characteristics, different indices will be combined, according to their high correlation with annoyance ratings. First, the spectral domain was divided into two parts with N_{1-12} for spectral content at low and medium frequencies and with $TETC_{13-18}$ for tonal components at high frequencies. Therefore, both indices can be combined in a model, as the partial correlation between annoyance and $TETC_{13-18}$ adjusted for N_{1-12} is high and significant (r=0.92, $p<0.01$).

Then, correlation coefficients obtained for the indices R and F are surprisingly high as an analysis of modulation spectra of different aircraft flyover noises did not explain this good correlation by the presence of modulation frequencies in most annoying flyover noises. For example, Figures 5.6 and 5.7 represent the modulation index spectrogram of the aircraft flyover noises a2 and a6, respectively one of the least and one of the most annoying aircraft flyover noise. The modulation index is derived from the instantaneous amplitude of the analytical signal with the help of the Hilbert transform.

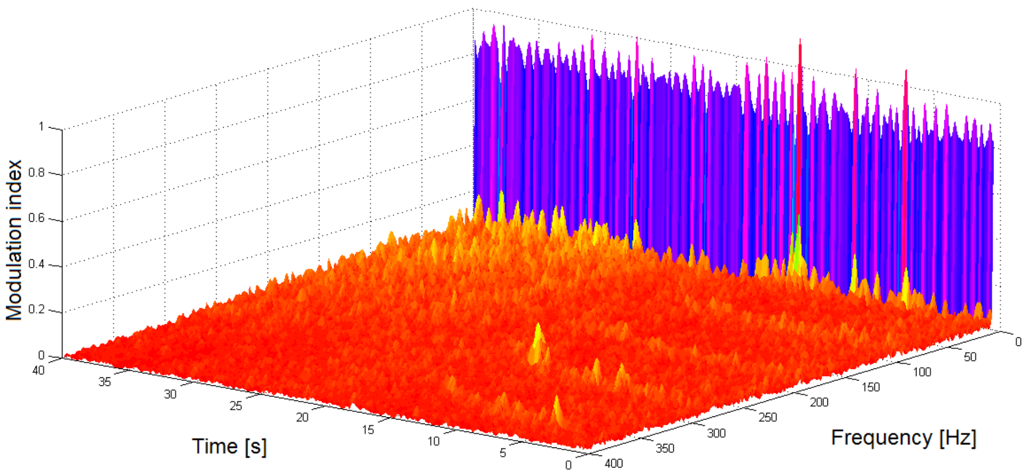

Figure 5.7: Modulation index spectrogram of a6, one of the most annoying aircraft noises of the experiment.

For the aircraft flyover noise a2, two modulation frequency ranges appear: the first one around 130 Hz, with a maximal modulation index of 0.6 and the second one around 260 Hz, with a maximal modulation index of 0.18. For the aircraft flyover noise a6, the presence of distinct modulation frequencies is less obvious. Indeed, four modulation frequencies are present (85 Hz and its three first harmonics) but their corresponding maximal modulation indices are very small, ranged from 0.1 to 0.2. The aircraft flyover noise a6 contains therefore less noticeable modulations than a2. Thus, the annoying character of aircraft flyover noise does not seem to be due to modulation phenomena. Furthermore, the analysis shows that the roughness index, calculated using the dBsonic software, that is to say based on Aures' model (*cf.* [?]), does not seem to be appropriate to quantify the modulation-related sensations of aircraft flyover noises, as the roughness index for a2 is the smallest one (R=10.4 cAsper) whereas the one for a6 is the highest one (R=21.6 cAsper). A comparison of the modulation spectrogram of a6, one of the most annoying aircraft flyover noises, with the one of a2, one of the least annoying aircraft flyover noises, shows therefore that the high correlation between annoyance and R is not relevant. As sound pressure level is involved in the calculation of R, the high correlation between annoyance and R may be due to the high correlation between annoyance and L_{Aeq}. This is confirmed by the partial correlation between annoyance and R adjusted for L_{Aeq}, which is not significant (r=0.36, p>0.05). The same analysis and conclusions hold for the fluctuation strength F. Thus, the indices R and F will be disregarded in the further approach.

Finally, the correlation coefficients obtained for the indices σ', VAP and $\sigma'(N)$ are surprising, too. Indeed, σ' is not correlated with annoyance, contrary to VAP and $\sigma'(N)$. However, the good correlation between annoyance and VAP may be explained by the good correlation between annoyance and L_{Aeq}, as VAP is based on L_{Aeq}. As a matter of fact, the partial correlation between annoyance and VAP adjusted for L_{Aeq} is not significant (r=0.05, p>0.05). Thus, VAP cannot be combined with L_{Aeq}, in order to construct an annoyance model. On the other hand, as the correlation between annoyance and $\sigma'(N)$ is higher than the one between annoyance and L_{Aeq}, the partial correlation between annoyance and L_{Aeq} adjusted for $\sigma'(N)$ was calculated. It appears to be not significant (r=-0.20, p>0.05). Thus, $\sigma'(N)$ and L_{Aeq} cannot be combined in the proposal of an annoyance model.

Therefore, four combinations of indices highly correlated with annoyance will be further considered as a baseline in the analysis in order to enhance annoyance modeling: i) N_{10} (to account for the loudest instantaneous perceived intensity during flyovers), ii) L_{Aeq} (to account for the equivalent sound pressure level), iii) N_{1-12} in combination with $TETC_{13-18}$ (to account for perceived intensity at low and medium frequencies and for tonal components in high frequencies) and iv) $\sigma'(N)$ (to account for temporal aspects such as global temporal variation and irregular amplitude variations).

2.4 Noise annoyance models based on multilevel regression

In order to consider both acoustical and individual variables in annoyance models, multilevel regression analysis will be performed, as done in Chapter 4, Section 2.3. Only multilevel regression equation and criteria to select models will be briefly presented hereinafter (for more details, see Chapter 4, Section 2.3 and [130, 131, 49]).

Model specification: As data were obtained from a repeated measure experiment, the first level of regression refers to stimuli (aircraft flyover noise, denoted as i in subscript) and the second level refers to individuals (denoted as j in subscript). Considering a model with one variable at individual level (the noise sensitivity, denoted as $Sens$) and M variables at stimulus level (denoted as $Index_m$), formulas are given as follows:

$$A_{ij} = \pi_{0j} + \sum_{m=1}^{M} \pi_{mj} Index_{mi} + e_{ij} \tag{5.1}$$

$$\pi_{0j} = \beta_{00} + \beta_{01} \times Sens_j + u_{0j} \tag{5.2}$$

$$\pi_{mj} = \beta_{m0} + \beta_{m1} \times Sens_j + u_{mj} \tag{5.3}$$

$$\begin{bmatrix} u_{0j} \\ \vdots \\ u_{mj} \\ \vdots \\ u_{Mj} \end{bmatrix} \backsim \mathcal{N}\left(0, \begin{bmatrix} \sigma^2_{u_0} & \cdots & \cdots & \cdots & \sigma_{u_{0M}} \\ \vdots & \ddots & \vdots & & \vdots \\ \sigma_{u_{m0}} & \cdots & \sigma^2_{u_m} & \cdots & \sigma_{u_{mM}} \\ \vdots & & \vdots & \ddots & \vdots \\ \sigma_{u_{M0}} & \cdots & \cdots & \cdots & \sigma^2_{u_M} \end{bmatrix}\right) \tag{5.4}$$

$$\text{for } m = 1, ..., M \text{ and for } j = 1, ..., J$$

$$e_{ij} \backsim \mathcal{N}(0, \sigma_e^2) \text{ for } i = 1, ..., I \text{ and } j = 1, ..., J$$

Computations: The computation of multilevel regression is Bayesian and inference about studied parameters are made using their Bayesian posterior distribution [49]. Posterior distributions of model parameters are approximated via Markov Chain Monte Carlo (MCMC) simulation, with 290,000 iterations. This simulation is performed using the multilevel model fitting software MLwiN, v2.31.

Model selection: In order to select the model which provides a better estimation of annoyance ratings, three criteria are used:

- R_1^2: proportion of variance explained at stimulus level. R_1^2 varies from 0 to 1. The closer R_1^2 is to 1, the better is the goodness-of-fit of the model estimates to the data.
- $R_{2,m}^2$ (m=0, …, M): proportion of variance explained at individual level. This criterion is computed for each random coefficient at stimulus level: the intercept π_{0j}

and the slopes π_{mj}. This criterion enables to evaluate if noise sensitivity explains variation of each random coefficient (π_{0j} or π_{mj}). $R^2_{2,m}$ varies from 0 to 1. The closer $R^2_{2,0}$ (calculated for the intercept π_{0j}) is to 1, the more noise sensitivity has an effect on individuals' mean rating. The closer $R^2_{2,m}$ (calculated for the random slope π_{mj}) is to 1, the more noise sensitivity has a moderating effect on the relationship between the m^{th} index and the annoyance ratings.

- Deviation Information Criterion (DIC): This criterion provides a measure of the out-of-sample predictive error [49]. The lower the DIC is, the better the predictive power of the model is. When comparing two models, differences in DIC of more than 10 might rule out the model with the higher DIC; differences between 5 and 10 are substantial; for a DIC difference less than 5, it could be misleading to report the model with the lower DIC [127].

Application to the experimental data set: First, two null models were tested: one without noise sensitivity at individual level (M0a) and one with noise sensitivity at individual level (M0b) (*cf.* Table 5.3).

Table 5.3: Null models M0a and M0b, respectively without and with noise sensitivity as individual-level explanatory variable. Coef. (95% CI): Coefficient and its 95% Bayesian credibility interval; 1^{st} Level: Stimulus Level; 2^{nd} Level: Individual Level.

Null model	M0a without sensitivity	M0b with sensitivity
	Coef. (95% CI)	Coef. (95% CI)
Fixed part		
β_{00} (Intercept)	4.35 (3.56; 5.16)	1.20 (-0.30; 2.71)
β_{01} (*Sens*)	–	0.60 (0.34; 0.86)
Random part		
σ^2_e (1^{st} Level)	2.23 (1.93; 2.58)	2.23 (1.93; 2.59)
σ^2_{u0} (2^{nd} Level)	5.12 (3.03; 8.53)	3.05 (1.75; 5.23)
Explained variance		
R^2_1 (1^{st} Level)	0.69	0.69
$R^2_{2,0}$ (2^{nd} Level)	–	0.40
DIC	1474	1473

For model M0b, $R^2_{2,0}$ reached 0.40 and β_{01} was significantly different from 0. Thus, noise sensitivity had an effect on the intercept π_{0j}, and hence on participants' mean annoyance rating: participants with high noise sensitivity gave high annoyance ratings. Noise sensitivity was therefore kept for intercept modeling and M0b was further used as a baseline.

In order to enhance annoyance modeling, indices characterizing different influential acoustical features were used. The selection of noise indices to be used in annoyance models was governed by both the analysis of verbalizations of the participants (*cf.* Section 2.1) and the analysis of the aircraft signals (*cf.* Sections 2.2 and 2.3). Several indices were tested using multilevel regression analysis. First, models using N_{10} or L_{Aeq} alone were studied (*cf.* Table 5.4), as 13 participants mentioned perceived sound intensity. Then, models using $\sigma'(N)$ were studied (*cf.* Table 5.5), as 18 participants mentioned global temporal variation. Finally, the indices N_{1-12} and $TETC_{13-18}$ were also studied to propose models (*cf.* Table 5.5), as 19 participants mentioned spectral content (*cf.* Section 2.3).

First, two-level regression models were built with one single index as a stimulus-level explanatory variable. The loudness exceeded 10% of the time N_{10} is considered as single index at stimulus level. Three types of single-index model were studied: i) model $N_{10} - fix$ with π_{1j} as fixed slope, only equal to β_{10} (see Equation (5.3)), ii) model $N_{10} - rand$ with π_{1j} $(= \beta_{10} + u_{1j})$ considered as random slope and iii) model $N_{10} - mod$ with π_{1j} as a random slope using noise sensitivity (see Equation (5.3)) in order to test the moderating effect of noise sensitivity on the relationship between noise annoyance and N_{10}. For models with L_{Aeq}, the same rationale was applied. The results are shown in Table 5.4. The indices at stimulus level are grand-mean centered. Standardized coefficients were calculated using the z-scores of all variables, in order to compare the contribution of each index to the model estimates.

Table 5.4: Multilevel models involving N_{10} with a fixed slope, with a random slope and with a moderating effect and L_{Aeq} with a random slope and with a moderating effect. The values of N_{10} and L_{Aeq} are grand mean centered with the grand-mean 8 sones and 50.19 dB(A) computed across the studied stimuli. Coef. (95% CI): Coefficient and its 95% Bayesian credibility interval; [*St. Coef. (95% CI)*]: Standardized Coefficient and its 95% Bayesian credibility interval; 1^{st} Level: Stimulus Level; 2^{nd} Level: Individual Level. The covariances between residual errors at individual level are not shown.

Model:	$N_{10} - fix$	$N_{10} - rand$	$N_{10} - mod$	$L_{\text{Aeq}} - rand$	$L_{\text{Aeq}} - mod$
Index:	N_{10}	N_{10}	N_{10}	L_{Aeq}	L_{Aeq}
Slope:	fixed slope	random slope	moderating effect	random slope	moderating effect
	Coef. (95% CI) [*St. Coef. (95% CI)*]	Coef. (95% CI) [*St. Coef. (95% CI)*]	Coef. (95% CI) [*St. Coef. (95% CI)*]	Coef. (95% CI) [*St. Coef. (95% CI)*]	Coef. (95% CI) [*St. Coef. (95% CI)*]
Fixed part					
β_{00} (Intercept)	1.20 (-0.36; 2.75)	1.31 (-0.27; 2.93)	1.22 (-0.30; 2.79)	1.30 (-0.30; 2.94)	1.22 (-0.30; 2.79)
β_{01} (*Sens*)	0.60 (0.33; 0.87)	0.58 (0.30; 0.86)	0.60 (0.33; 0.86)	0.58 (0.30; 0.86)	0.60 (0.33; 0.86)
	[0.54 (0.30; 0.78)]	[0.52 (0.27; 0.78)]	[0.53 (0.30; 0.77)]	[*0.52 (0.27; 0.78)*]	[*0.53 (0.29; 0.78)*]
β_{10} (*Index*)	0.43 (0.38; 0.48)	0.43 (0.35; 0.52)	0.25 (0.06; 0.45)	0.24 (0.19; 0.28)	0.13 (0.02; 0.23)
	[0.35 (0.30; 0.39)]	[0.35 (0.28; 0.41)]	[0.35 (0.28; 0.41)]	[*0.34 (0.27; 0.41)*]	[*0.34 (0.28; 0.40)*]
β_{11} (*Index* × *Sens*)	–	–	0.03 (0.00; 0.07)	–	0.02 (0.002; 0.04)
	–	–	[0.06 (-0.001; 0.13)]	–	[*0.07 (0.01; 0.13)*]
Random part					
σ_e^2 (1^{st} Level)	1.34 (1.15; 1.55)	1.17 (1.01; 1.37)	1.18 (1.00; 1.37)	1.23 (1.06; 1.44)	1.23 (1.06; 1.43)
	[0.20 (0.17; 0.23)]	[0.17 (0.15; 0.20)]	[0.17 (0.15; 0.20)]	[*0.18 (0.15; 0.21)*]	[*0.18 (0.15; 0.21)*]
σ_{u0}^2 (2^{nd} Level)	3.14 (1.84; 5.29)	3.24 (1.92; 5.39)	3.23 (1.93; 5.41)	3.24 (1.92; 5.39)	3.23 (1.92; 5.39)
	[0.46 (0.27; 0.77)]	[0.47 (0.28; 0.79)]	[0.47 (0.28; 0.78)]	[*0.47 (0.28; 0.79)*]	[*0.47 (0.28; 0.78)*]
σ_{u1}^2 (2^{nd} Level)	–	0.04 (0.02; 0.08)	0.03 (0.01; 0.07)	0.01 (0.004; 0.02)	0.008 (0.003; 0.018)
	–	[0.03 (0.01; 0.05)]	[0.02 (0.01; 0.04)]	[*0.02 (0.01; 0.04)*]	[*0.02 (0.01; 0.04)*]
Explained variance					
R_1^2 (1^{st} Level)	0.81	0.83	0.83	0.82	0.82
$R_{2,0}^2$ (2^{nd} Level)	0.40	0.39	0.39	0.39	0.40
$R_{2,1}^2$ (2^{nd} Level)	–	0	0.17	–	0.23
DIC	1272	1240	1240	1258	1257

Both models $N_{10} - fix$ and $N_{10} - rand$ outperformed the null model M0b (DIC was decreased by around 200). Furthermore, the random slope slightly improved the goodness-of-fit of the model (R_1^2 was increased by 2%) and the out-of-sample predictive error (DIC was decreased by 32). For model $N_{10} - mod$, cross-level interaction coefficient, β_{11}, between N_{10} and noise sensitivity, was not significantly different from zero. Thus, noise sensitivity did not appear to have a moderating effect on the relationship between N_{10} and noise annoyance. Despite the value of $R_{2,1}^2$, noise sensitivity was not conserved for further modeling of the slope π_{1j} for N_{10}.

For models based on L_{Aeq} [5], only the best combinations were kept, according to DIC and $R_{2,1}^2$ criteria: i) L_{Aeq} with random slope (model $L_{\text{Aeq}} - rand$), and ii) L_{Aeq} with moderating effect (model $L_{\text{Aeq}} - mod$). All slope coefficients were significantly different from 0 and should therefore be kept. Contrary to the model $N_{10} - mod$, the interaction term is significant in $L_{\text{Aeq}} - mod$. The difference in DIC value between the models $L_{\text{Aeq}} - rand$ and $L_{\text{Aeq}} - mod$ is not significant but 23% of the variance at the individual level is explained by the introduction of noise sensitivity within the slope.

Using standardized coefficients [6], the contribution of each variable to the model can be determined. Noise sensitivity highly contributed to the models (61% for $N_{10} - fix$, 60% for $N_{10} - rand$ and $L_{\text{Aeq}} - rand$ and 56% for $L_{\text{Aeq}} - mod$). Furthermore, the interaction term between noise sensitivity and L_{Aeq} contributed for 6% to the models, which increased the contribution of noise sensitivity to the model.

The same rationale applied by considering two-level regression models using $\sigma'(N)$ and the combination of N_{1-12} and $TETC_{13-18}$ (*cf.* Table 5.5). The best combinations were kept, according to DIC and $R_{2,1}^2$ criteria: i) $\sigma'(N)$ with random slope (model $\sigma'(N) - rand$), ii) $\sigma'(N)$ with moderating effect (model $\sigma'(N) - mod$) and iii) N_{1-12} and $TETC_{13-18}$ with random slope (model $LMLHT - rand$, for "Low and Medium frequency Loudness and High frequency Tonal component - random slope").

All slope coefficients were significantly different from 0 and should therefore be kept. Contrary to the model $N_{10} - mod$, the interaction term is significant in the model $\sigma'(N) - mod$. The difference in DIC value between the models $\sigma'(N) - rand$ and $\sigma'(N) - mod$ is not significant but 21% of the variance at the individual level are explained by the introduction of noise sensitivity within the slope.

Using standardized coefficients, the contribution of each variable to the model can be determined. Noise sensitivity highly contributed to the three models (60% for $\sigma'(N) - rand$, 56% for $\sigma'(N) - mod$ and 57% for $LMLHT - rand$). In particular, the interaction term between noise sensitivity and noise index contributed to the model (7% for $\sigma'(N) - mod$), which increased also the contribution of noise sensitivity to the model. This highlights the importance to consider explanatory variables at individual level in annoyance models.

5. When studying two-level model using L_{Aeq} without noise sensitivity and without an individual error term in the intercept, as done by Miedema and Oudshoorn [82], the R_1^2 is equal to 0.12, which is the part of the variance at the first level explained by L_{Aeq}.

6. The contribution of each variable to the model is calculated by dividing the corresponding standardized coefficient by the sum of all standardized coefficients.

Table 5.5: Multilevel models involving $\sigma'(N)$ on one hand, N_{1-12} and $TETC_{13-18}$ on the other hand. The values of $\sigma'(N)$, N_{1-12} and $TETC_{13-18}$ are grand-mean centered with the respective grand mean 27.47 sone/s, 3.10 sones and 43.94 dB computed across the studied stimuli. Coef. (95% CI): Coefficient and its 95% Bayesian credibility interval; [*St. Coef. (95% CI)*]: Standardized Coefficient and its 95% Bayesian credibility interval; 1^{st} Level: Stimulus Level; 2^{nd} Level: Individual Level. The covariances between residual errors at individual level are not shown.

Model:	$\sigma'(N) - rand$	$\sigma'(N) - mod$	$LMLHT - rand$
Index:	$\sigma'(N)$	$\sigma'(N)$	N_{1-12} & $TETC_{13-18}$
Slope:	random slope	moderating effect	random slope
	Coef. (95% CI)	Coef. (95% CI)	Coef. (95% CI)
	[*St. Coef. (95% CI)*]	[*St. Coef. (95% CI)*]	[*St. Coef. (95% CI)*]
Fixed part			
β_{00} (Intercept)	1.29 (-0.37; 2.88)	1.22 (-0.33; 2.76)	1.31 (-0.27; 2.91)
β_{01} (*Sens*)	0.58 (0.30; 0.87)	0.60 (0.33; 0.87)	0.58 (0.30; 0.86)
	[*0.52 (0.27; 0.78)*]	[*0.53 (0.30; 0.78)*]	[*0.52 (0.27; 0.77)*]
β_{10} (*Index* 1:	0.15 (0.12; 0.18)	0.08 (0.01; 0.15)	0.09 (0.05; 0.12)
$\sigma'(N)$ or $TETC_{13-18}$)	[*0.35 (0.28; 0.41)*]	[*0.35 (0.28; 0.41)*]	[*0.19 (0.11; 0.26)*]
β_{20} (*Index* 2: N_{1-12})	–	–	0.75 (0.57; 0.94)
	–	–	[*0.21 (0.15; 0.23)*]
β_{11} (*Sens* × *Index* 1)	–	0.01 (0.001; 0.02)	–
	–	[*0.07 (0.007; 0.14)*]	–
Random part			
σ^2_e (1^{st} Level)	1.17 (1.00; 1.36)	1.17 (1.00; 1.37)	1.20 (1.03; 1.39)
	[*0.17 (0.15; 0.20)*]	[*0.17 (0.15; 0.20)*]	[*0.17 (0.15; 0.20)*]
σ^2_{u0} (2^{nd} Level)	3.24 (1.92; 5.42)	3.23 (1.92; 5.40)	3.24 (1.93; 5.38)
	[*0.47 (0.28; 0.78)*]	[*0.47 (0.28; 0.78)*]	[*0.47 (0.28; 0.78)*]
σ^2_{u1} (2^{nd} Level)	0.004 (0.002; 0.009)	0.004 (0.001; 0.007)	0.005 (0.002; 0.010)
	[*0.03 (0.01; 0.05)*]	[*0.02 (0.01; 0.04)*]	[*0.02 (0.01; 0.04)*]
Explained variance			
R^2_1 (1^{st} Level)	0.83	0.83	0.83
$R^2_{2,0}$ (2^{nd} Level)	0.39	0.39	0.39
$R^2_{2,1}$ (2^{nd} Level)	–	0.21	–
DIC	1239	1238	1248

Moreover, although high frequency content was more often mentioned by the participants compared to low frequency content (*cf.* Section 2.1), the contributions of N_{1-12} and $TETC_{13-18}$ to the model $LMLHT - rand$ were very similar (21% for N_{1-12} and 22% for $TETC_{13-18}$).

All these models led to similar results, both in terms of DIC value and in terms of explained variance. Two-level regression models using combination of all these relevant indices accounting for different acoustical features were considered (*e.g.* N_{10} combined with $\sigma'(N)$, $\sigma'(N)$ combined with N_{1-12} and $TETC_{13-18}$, etc.). Such two-level regression models did not allow to enhance the previously tested models.

3 Discussion

Noise annoyance due to aircraft flyover noises was assessed under laboratory conditions. The main objectives were: i) to identify acoustical features influencing noise annoyance, ii) to characterize them using appropriate indices and iii) to take them and the individual noise sensitivity into account to improve annoyance modeling.

The procedure of noise annoyance assessment with imaginary context in laboratory and without activity was selected. Actually, such procedure was already used in literature to evaluate noise annoyance due to urban road pass-by noises heard in presence of industrial noise [91]. This procedure was compared to an experiment in simulated environment. The latter experiment was performed in simulated living-room in laboratory, with different relaxing activities, to evaluate noise annoyance due to urban road traffic noise heard in presence of industrial noise [76]. The annoyance models developed in both studies were tested using *in situ* data of noise annoyance due to road traffic noise combined with industrial noise [87]. They provided similar results in terms of prediction quality ([87], see also [**?**] for another comparison of laboratory experiments with imaginary context and with simulated context).

The verbalization task enables to highlight three main acoustical features of aircraft flyover noises: i) spectral content, ii) global temporal variation and iii) perceived sound intensity. The same acoustical features were also previously highlighted by Barbot *et al.* [3] concerning the acoustical perceptual representation of aircraft noises and are well-known to influence noise annoyance [77, 130, 61, 94, 93]. However, up to now, annoyance models for aircraft noise only took into account energy-based indices and indices related to the irregular amplitude variation (*e.g.* σ' based on sound pressure level [94]). In the past, no indices were involved to consider the spectral content, despite it was the most often cited acoustical feature by the participants in previous studies (*e.g.* [3]) as well as in the current study.

A correlation analysis showed that the energy-based index L_{Aeq} was highly correlated with annoyance, similar as N_{10}, the loudness exceeded 10% of the time, as well as N_{1-12}, which accounts for the perceived intensity at low and medium frequencies, and $TETC_{13-18}$, which accounts for the tonal components at high frequencies (*i.e.* the spectral content of the noise). On the other hand, the indices $\sigma'(N)$ and VAP, which account for irregular temporal variation of the noises, R and F, which account for regular temporal variation of the noise, highly correlated with annoyance. However, the high correlations of VAP, R and F with annoyance were due to the high correlation between annoyance and L_{Aeq}, as these indices were computed using an energy-based index.

Multilevel regressions were performed in order to propose relevant combinations of noise indices coupled with noise sensitivity to enhance annoyance modeling. Four combinations of the previous relevant indices were considered: i) N_{10}, ii) L_{Aeq}, iii) $\sigma'(N)$ and iv) N_{1-12} and $TETC_{13-18}$. Noise sensitivity was introduced as explanatory variable at individual level. Four combinations of indices $N_{10} - rand$, $L_{\text{Aeq}} - rand$, $\sigma'(N) - rand$ and $LMLHT - rand$ *i.e.* with random slope led to comparable goodness-of-fits of the models and out-of-sample predictive errors. It is therefore not possible to conclude whether a model is better than another one. Only a comparison of these models using new data, and in particular *in situ* data, could enable to choose one model. In all models, the contribution of noise sensitivity also turned out to be significant in the intercept equation (*cf.* Equation 2), as was found by Trollé *et al.* [130, 131]. A moderating effect was appeared in model $L_{\text{Aeq}} - mod$ between L_{Aeq} and noise sensitivity and in model $\sigma'(N) - rand$ between $\sigma'(N)$ and noise sensitivity. In the same manner, some authors identified a moderating effect for *in situ* road and aircraft noises (*e.g.* [84]) whereas some other authors did not find a moderating effect neither for tramway noise (*e.g.* [117, 130, 131]) in laboratory conditions nor for *in situ* aircraft noise (*e.g.* [133]).

Furthermore, noise sensitivity contributed more than 50% to the annoyance models developed in the current study. Studying aircraft noise annoyance, Taylor [125] confirmed that noise sensitivity had the strongest effect on annoyance. To improve predictive accuracy in the future, these results clearly encourage the integration of noise sensitivity in noise annoyance models that are to be employed in *in situ* studies. In order to validate these relevant combinations of indices, noise sensitivity should be collected during *in situ* surveys, as was already done in former studies dealing with aircraft noise annoyance (*e.g.* [4, 125]).

4 Conclusion

The main objectives of this study were to identify and characterize influential acoustical factors of noise annoyance and to test them with an influential non-acoustical factor, the noise sensitivity, in order to enhance noise annoyance models. This study focused on noise annoyance due to aircraft flyover noises.

The most often cited acoustical features of aircraft noise were: the spectral content, the temporal variation and the perceived sound intensity. Noise indices which enable to characterize these acoustical features as well as the individual noise sensitivity were introduced in multilevel regression to model noise annoyance. Noise sensitivity was found to highly contribute to the models. Moreover, for two out of the four combinations of indices studied, noise sensitivity had a moderating effect on the relationship between the noise index and the noise annoyance. This highlights that this individual factor has to be considered in future studies dealing with noise annoyance due to aircraft noise in order to improve the prediction accuracy of noise annoyance models.

In this study, four combinations of indices led to models with comparable goodness-of-fit of the models and out-of-sample predictive errors. Future survey data can serve to assess the predictive power of the models.

Résumé des principaux résultats

♣ Les caractéristiques acoustiques les plus citées pour le bruit de passage d'avion sont le contenu spectral, les fluctuations irrégulières d'amplitude, et l'intensité sonore perçue.
♣ Une régression multi-niveau a été utilisée pour modéliser la gêne en considérant à la fois la sensibilité au bruit et des combinaisons d'indices relatifs aux caractéristiques acoustiques les plus citées.
♣ La sensibilité au bruit contribue fortement aux modèles de gêne, avec un effet modérateur sur la relation entre la gêne et les indices acoustiques pour 2 des 4 combinaisons d'indices.

Et après ?

Ce chapitre a montré l'influence sur la gêne de 3 caractéristiques acoustiques du bruit d'avion. Des indices permettant de rendre compte de ces caractéristiques acoustiques ont été introduits dans des modèles de gêne, ainsi que la sensibilité au bruit, conformément aux résultats du Chapitre 2.

Les bruits d'avion étudiés dans ce chapitre vont être utilisés dans le Chapitre 6 afin d'étudier la gêne en situation de multi-exposition aux bruits de trafic routier urbain et d'avion. De plus, les résultats de ce chapitre serviront de base à l'analyse des données de gêne du Chapitre 6.

Chapitre 6

Caractérisation physique et perceptive de différentes situations de multi-exposition aux bruits de trafic routier et d'avion en laboratoire et *in situ*

Questions scientifiques

Les questions auxquelles nous souhaitons répondre dans ce chapitre sont les suivantes :

- ♣ quels sont les facteurs acoustiques qui influencent la gêne partielle due au bruit de trafic routier urbain entendu en présence de bruit d'avion ? Ces facteurs sont-ils les mêmes que lorsque le bruit de trafic routier urbain est entendu seul ?
- ♣ quels sont les facteurs acoustiques qui influencent la gêne partielle due au bruit d'avion entendu en présence de bruit de trafic routier urbain ? Ces facteurs sont-ils les mêmes que lorsque le bruit d'avion est entendu seul ?
- ♣ les combinaisons d'indices acoustiques proposées aux Chapitres 4 et 5 demeurent-elles pertinentes pour caractériser les gênes partielles dues aux bruits du trafic routier urbain et d'avion ?
- ♣ les modèles établis en laboratoire permettent-ils de prédire les gênes partielles mesurées *in situ* ?
- ♣ comment les gênes partielles influencent-elles la gêne totale ?
- ♣ quels modèles de gêne totale de la littérature permettent le meilleur calcul de gêne totale évaluée en laboratoire ? Les résultats sont-ils les mêmes lorsque les modèles construits en laboratoire sont confrontés à des données collectées *in situ* ?

Après avoir étudié en conditions contrôlées les situations de mono-exposition au bruit de trafic routier urbain (*cf.* Chapitre 4) puis au bruit d'avion (*cf.* Chapitre 5), une expérience avec mise en situation a été réalisée afin de caractériser les situations de multi-exposition à ces 2 types de bruit. Cette caractérisation consiste à mettre en évidence les phénomènes perceptifs influant la gêne sonore et à proposer des indicateurs caractéristiques de la gêne en situation de multi-exposition à ces bruits. Les modèles construits à partir des données recueillies en laboratoire sont confrontés aux données de gêne collectées lors de l'enquête *in situ*, présentée au Chapitre 2.

Introduction

Both specific noise annoyance due to urban road traffic noise and noise annoyance due to aircraft flyover noise were studied under laboratory conditions (*cf.* Chapters 4 and 5, respectively). Their acoustical features influencing specific noise annoyance were identified and characterized, on the basis of different noise indices. Noise annoyance was calculated using multilevel regression involving both combinations of noise indices and an individual characteristic: noise sensitivity. However, in urban areas, aircraft noise is often not heard in isolation, but with other noise sources, such as urban road traffic noise. These noises may therefore interact with each other, in particular in terms of noise annoyance. Understanding and modeling of annoyance due to these combined noises are of great importance for combined noise exposure management.

In the following, noise annoyance due to combined urban road traffic noise and aircraft noise is studied. Therefore, an experiment was carried out in a simulated environment (*cf.* Section 1). Partial and total annoyance were measured, as in the *in situ* survey, previously presented (*cf.* Chapter 2). Data of the different experiments presented in Chapters 4, 5 and 6 were aggregated to construct annoyance models for each noise source (*cf.* Sections 2.2.1 and 2.2.2) as done in literature for survey data (*e.g.* [82]). Total annoyance models for combined urban road traffic noise and aircraft noise were constructed using data of the combined noise experiment presented in Chapter 6 (*cf.* Section 2.5). The data of the *in situ* survey were used to test the proposed models for partial annoyances (*cf.* Section 2.4) and for total annoyance (*cf.* Section 2.6). In order to carry out model testing, a methodology was proposed (*cf.* Section 2.3) to estimate the values of the different noise indices used in models from the *in situ* values of the index L_{den} allocated to each survey respondent.

1 Method of the laboratory experiment

1.1 Apparatus

The experiment took place in a quiet simulated living-room (*cf.* Figure 6.1), with a background noise level below 22 dB(A). The noise sequences were reproduced employing a 2.1 audio reproduction system consisting of two active loudspeakers (Dynaudio Acoustics BM5A) and one active subwoofer (Dynaudio Acoustics BM9S).

An artificial head (Cortex MK2/NCF1) and an omnidirectrional microphone (GRAS 40AE) were placed at participant's position in order to record the noise sequences. From sequence recordings, acoustic and psychoacoustic indices were calculated using MATLAB © and dBSonic software (ACOEM).

Figure 6.1: Photography of the simulated living room.

1.2 Stimuli

Under simulated environment conditions, studied noise sequences are longer than the ones studied under imaginary situation conditions. In order to reduce experiment total duration and participants' tiredness, total number of stimuli to be evaluated has to be limited. Therefore, the number of configurations for each noise source has to be limited too. It follows that, according to the recommendations given by Berglund and Nilsson [12], stimuli were constructed on the basis of a complete matrix composed of 4 aircraft noise sequences and 4 urban road traffic noise sequences. Sixteen noise sequences were therefore constructed. They lasted for 6 minutes (*i.e.* twice as long as the noise sequences of urban road traffic evaluated under imaginary situation in Chapter 4) to enable different urban road traffic noise scenarii and different aircraft flyover scenarii.

1.2.1 Urban road traffic noise sequences

In order to account for urban road traffic observed in cities where the survey was carried on, mean daily traffic in city streets and noise exposure expressed in terms of L_{den} were considered. These data allowed to select the traffic sequences 1T5 and 1T8 built in Chapter 4 in order to simulate noise exposure in the small streets, for which L_{den} ranged from 55 to 65 dB(A). Following the same rationale, the traffic sequences 2T8 and 2T11 were selected as they enable to simulate the noise exposure in bigger streets, for which L_{den} ranged from 65 to 75 dB(A). In order to construct combined noise sequences of 6 min, 3-min urban road traffic sequences stemming from Chapter 4 were played twice in a combined noise sequence.

1.2.2 Aircraft noise sequences

In order to reproduce the aircraft traffic observed in cities where the survey was carried on, aircraft noise sequences were composed of 1 to 4 aircraft flyover noises (that is, 10 to 40 aircraft flyovers per hour, which corresponds to an interval between 2 aircraft flyovers ranging from 90 s to 6 min). Aircraft flyover noises composing the sequences stemmed from the experiment presented in Chapter 5. Four different aircraft noises were selected, according to their mean annoyance rating (*cf.* Figure 5.1). Aircraft flyover noises a2 and a6 were selected as they are respectively one of the least and one of the most annoying flyover noises. Then, two other aircraft flyover noises (a7 and a11) were selected within the ones getting mean annoyance rating significantly different from a2 and a6.

Table 6.1 gives the succession of aircraft flyover noises and the interval between 2 aircraft flyover events.

Table 6.1: Aircraft noise sequences and the interval between 2 aircraft flyover events.

Succession of the aircraft flyover noises	Interval between 2 events
a2	
a2 + a6	3 min
a2 + a7 + a6	2 min
a2 + a7 + a11 + a6	1 min 30 s

1.2.3 Combined noise sequences

The combined noise sequences were composed of an aircraft noise sequence, an urban road traffic noise sequence and an urban background noise.

An urban background noise, recorded by Trollé *et al.* [130, 131] early in the morning without distinguishable noise events, was equalized at 32.4 dB(A).

Noise level of aircraft and of urban road traffic noise sequences was 20 dB(A) lower than the *in situ* observations. This was done in order to simulate a window partially-open and a distance between the street and the living-room. Such noise reduction over the noise sequences enables a given single road vehicle pass-by noise to be played at the same noise level in the different combined noise sequences.

Table 6.2 gives the A-weighted equivalent sound pressure level, L_{Aeq} [1], for the urban road traffic noise sequences combined with the urban background noise and for the aircraft flyover noises composing the aircraft noise sequences.

Table 6.3 gives the A-weighted equivalent sound pressure level over 6 min, $L_{Aeq,6min}$, of the combined noise sequences, obtained by combining the urban road traffic noise sequences with the aircraft noise sequences.

1. L_{Aeq} is calculated over the duration of the noise sequence.

Table 6.2: A-weighted equivalent sound pressure level over 6 min $L_{Aeq,6min}$ for the urban road traffic noise sequences and A-weighted equivalent sound pressure level over aircraft flyover duration $L_{Aeq,flyover}$ for the aircraft flyover noises composing the aircraft noise sequences.

$L_{Aeq,6min}$ for urban road traffic noise dB(A)		$L_{Aeq,flyover}$ for aircraft flyover noise dB(A)	
1T5	45.7	a2	35.0
1T8	46.6	a6	55.6
2T8	49.5	a7	51.3
2T11	51.9	a11	46.5

Table 6.3: A-weighted equivalent sound pressure level $L_{Aeq,6min}$ of the combined noise sequences

$L_{Aeq,6min}$ dB(A)		Aircraft noise sequence			
		a2	a2 + a6	a2 + a7 + a6	a2 + a7 + a11 + a6
Urban road	1T5	45.9	49.1	49.9	50.0
traffic noise	1T8	46.7	49.4	50.4	50.3
sequence	2T8	49.5	51.1	51.6	51.8
	2T11	52.0	53.0	53.3	53.4

1.3 Procedure

Three participants could perform the test simultaneously. They were asked to not speak together and to imagine themselves at home while relaxing during a reading activity. They could bring along their own reading stuff for the experiment. This procedure has been used in previous works (*e.g.* [76]). During the experiment, the stimuli were presented one by one in random order.

After each combined noise sequence, participants were asked about: i) the urban road traffic partial annoyance, ii) the aircraft partial annoyance and iii) the total annoyance due to combined noises: *"While you imagined yourself at home, while relaxing with this soundscape sequence, does (the road traffic noise) / (the aircraft noise) / (the global noise due to the road traffic noise and to the aircraft noise) annoy you?"* (*"Lorsque vous vous imaginiez chez vous, en train de vous relaxer, en présence de cette séquence d'environnement sonore, (le bruit de la circulation routière) /(le bruit des avions) / (le bruit global dû au bruit de la circulation routière et au bruit des avions) vous a-t-il gêné ?"*). To answer to these 3 questions, participants gave their ratings on continuous scales ranging from "0" to "10", with 11 evenly spaced numerical labels and two verbal labels at both ends (*"not at all annoyed"* (*"Pas du tout gêné"*) and *"extremely annoyed"* (*"Extrêmement gêné"*)).

At the end of the experiment, participants answered the three following questions: *"Did (the aircraft noise) / (the road traffic noise) seem to be familiar to you?"* (*"Est-ce que (le bruit des avions) / (le bruit de la circulation routière) vous a paru familier?"*), *"How would you describe (the aircraft noise) / (the road traffic noise)? "* (*"Comment décririez-vous (le bruit des avions) / (le bruit de la circulation routière)?"*) and *"In a general way, how do* *you judge (the aircraft noise) / (the road traffic noise)? "* (*"De manière générale, comment jugez-vous (le bruit des avions) / (le bruit de la circulation routière)? "*). Then, they filled in a questionnaire (similar to the one given in Appendix A, Section 1) with personal items such as non-acoustical factors. For noise sensitivity, participants were asked: *"Would you say you are sensitive to noise in a general way?"* (*"Diriez-vous que vous êtes sensible au bruit en général? "*) and they had to make a judgment on a continuous scale ranging from "0" to "10" with two verbal labels at both ends (*"not at all sensitive"* (*"Pas du tout sensible"*) and *"extremely sensitive"* (*"Extrêmement sensible"*)). The experiment was lasting for two hours.

1.4 Participants

The experiment was performed by 32 participants (17 male, 15 female) aged between 20 and 67 years (mean age = 37.5; standard deviation = 14.5). All participants declared normal hearing abilities and were paid for their participation.

2 Results

In this section, data stemming from experiments presented in Chapter 4 to 6 will be used to construct annoyance models for urban road traffic noise and for aircraft noise. These models and total annoyance models from literature (*cf.* Chapter 1, Section 3.3) will be used to propose annoyance models for the combination of both noises. Data collected during the survey will be used to test the models established under laboratory conditions.

Firstly, the verbalizations collected during combined noise experiment will be compared with the ones obtained in Chapters 4 and 5. Indeed, due to the combination of noises, some masking or synergistic effects can occur, modifying the main influential acoustical features.

Secondly, noise annoyance models for single exposures will be constructed on the basis of multilevel regression. Therefore, the data from several experiments will be aggregated as done in literature (*cf.* [82]): i) for urban road traffic noise, data from current experiment will be aggregated with the ones from the experiment presented in Chapter 4, and ii) for aircraft noise, data from current experiment will be aggregated with the ones from the experiment presented in Chapter 5. To aggregate the results of different experiments, partial and specific annoyances are considered as equivalent. This hypothesis is done on the basis of the results of Klein [60]: partial annoyance was satisfactorily predicted on the basis of indicators previously developed for specific annoyance. Furthermore, such aggregation of measured partial and specific annoyances was already made in literature (*cf.* [82]).

Thirdly, evolution of relevant noise indices with noise level of each source in isolation (*e.g.* urban road traffic noise or aircraft noise) will be studied. This will enable to estimate the values of these noise indices from the L_{den} value of the corresponding source to which each respondent of the survey is exposed. Fourthly, such estimation will enable to test single noise annoyance models by comparing calculated annoyance with *in situ* measured annoyance.

Fifthly, total noise annoyance models will be constructed using single noise annoyance models (constructed in the second step just mentioned before) and data from combined noise experiment. Finally, these total noise annoyance models will be tested comparing calculated total annoyance with the measured one.

2.1 Verbalizations collected during the combined noise experiment

Concerning urban road traffic noise, i) 21 out of the 32 participants (66%) mentioned presence of PTWs within the sequences ("*moto*" ("*motorbike*"), "*mobylette*" ("*moped*"), "*scooter*" ("*scooter*")), ii) 18 out of the 32 participants (56%) mentioned global temporal variation ("*route = constante*" ("*road = constant*"), "*ils sont brefs*" ("*they are short*"), "*bruit rapide*" ("*quick noise*")), iii) 6 out of the 32 participants (19%) mentioned perceived sound intensity ("*peu d'intensité*" ("*few intensity*"), "*plus ou moins fort*" ("*more or less loud*"), "*volume élevé*" ("*high volume*")), and iv) 4 of the 32 participants (13%) mentioned timbre ("*son strident*" ("*strident sound*"), "*pétaradant*" ("*sputtering*"), "*crissement des freins*" ("*brake squeaking*")).

Concerning aircraft noise, i) 19 out of the 32 participants (59%) mentioned global temporal variation ("*avions : longs et pénibles*" ("*aircrafts: long and difficult*"), "*assez brefs*" ("*short enough*"), "*il évolue progressivement*" ("*it progressively flies*")), ii) 14 out of the 32 participants (44%) mentioned perceived sound intensity ("*bruit très gênant lorsque le niveau est élevé*" ("*noise very annoying when the level is high*"), "*sortant bien du bruit ambiant*" ("*significantly emerging from the surrounding noise*"), "*bruit puissant*" ("*powerful noise*")), and iii) 8 of the 32 participants (25%) mentioned timbre ("*comme un sifflement aïgu*" ("*like a high-pitched whistling*"), "*sourd*" ("*muffled*"), "*plutôt grave*" ("*rather deep*")).

In Table 6.4, the verbalizations of participants within different experiments are compared.

Table 6.4: Main verbalizations of the participants about urban road traffic and aircraft noises within different experiments (separated by a year), frequency of occurrences and number of participants.

	Single noise experiments Urban road traffic : 34 participants Aircraft : 33 participants	Combined noise experiment 32 participants	Information
Urban road traffic	Presence of PTWs (100%) Perceived noise intensity (56%) Global temporal variation (56%) Spectral content (24%) Modulation-related sensations (6%)	Presence of PTWs (66%) Global temporal variation (56%) Perceived noise intensity (19%) Timbre (13%)	8 common participants
Aircraft	Spectral content (58%) Global temporal variation (55%) Perceived noise intensity (39%)	Global temporal variation (59%) Perceived noise intensity (44%) Timbre (25%)	6 common participants

Highlighted influential features are similar in the different experiments. A deep analysis shows that occurrence frequency may be different from single noise experiment to combined noise experiment. Actually, for urban road traffic noise, only global temporal variation was as frequently cited in both experiments: all the other acoustical features were less frequently cited in combined experiment than in urban road traffic experiment (*cf.* Chapter 4). For aircraft noise, both global temporal variation and perceived noise intensity were as much cited in both experiments. Only timbre was less cited in combined experiment than in aircraft experiment (*cf.* Chapter 5). These differences in occurrence for timbre may be due to masking effects between the combined noise sources or due to participants' difficulty to describe acoustic content of combined noise source sequences whereas they were carrying out a reading activity. Nevertheless, this shows that main influential acoustical features remained the same.

2.2 Noise annoyance models based on multilevel regression for single noise exposures using laboratory data

In order to consider acoustical and individual data in annoyance models using data of different experiments, multilevel regression analysis will be performed. This regression method has been previously used for meta-analysis of *in situ* transportation noise annoyance studies without explanatory variable at the individual level [82] and for modeling annoyance data collected in laboratory conditions for tramway noises [130, 131], for urban road traffic noise (*cf.* Chapter 4) and for aircraft flyover noise (*cf.* Chapter 5) with explanatory variable at the individual level. Application of multilevel regression is well-suited to consider data from different experiments and to introduce both acoustical features and noise sensitivity in noise annoyance models. Multilevel regression will be briefly presented hereinafter (for more details, see [130, 131, 49]).

Model specification: As data were obtained from several repeated measure experiments, first level of regression model refers to the stimulus (urban road traffic noise sequence or aircraft noise sequence, denoted as i in subscript), second level refers to individual (denoted as j in subscript) and third level refers to experiment (denoted as k in subscript - neither variable nor error term is introduced in the model at this level). Considering a model with one variable at individual level (the noise sensitivity, denoted as $Sens$) and M variables at stimulus level (denoted as $Index_m$), formulas are as follows:

$$A_{ijk} = \pi_{0jk} + \sum_{m=1}^{M} \pi_{mjk} Index_{mi} + e_{ijk} \tag{6.1}$$

$$\pi_{0jk} = \beta_{000} + \beta_{011} \times Sens_{jk} + u_{0jk} \tag{6.2}$$

$$\pi_{mjk} = \beta_{m00} + \beta_{m11} \times Sens_{jk} + u_{mjk} \tag{6.3}$$

$$\begin{bmatrix} u_{0jk} \\ \vdots \\ u_{mjk} \\ \vdots \\ u_{Mjk} \end{bmatrix} \backsim \mathcal{N} \left(0, \begin{bmatrix} \sigma^2_{u_0} & \cdots & \cdots & \cdots & \sigma_{u_{0M}} \\ \vdots & \ddots & \vdots & & \vdots \\ \sigma_{u_{m0}} & \cdots & \sigma^2_{u_m} & \cdots & \sigma_{u_{mM}} \\ \vdots & & \vdots & \ddots & \vdots \\ \sigma_{u_{M0}} & \cdots & \cdots & \cdots & \sigma^2_{u_M} \end{bmatrix} \right) \tag{6.4}$$

$$\text{for } m = 1, ..., M, \text{ for } j = 1, ..., J \text{ and } k = 1, ..., K$$

$$e_{ijk} \backsim \mathcal{N}(0, \sigma^2_e) \text{ for } i = 1, ..., I, j = 1, ..., J \text{ and } k = 1, ..., K$$

Equation (6.1) is regression equation at stimulus level. A_{ijk} is the annoyance rating of individual j for stimulus i in experiment k. An individual can therefore have evaluated specific annoyance due to a noise sequence during one of the single noise experiments presented in Chapter 4 or 5 and partial annoyance due to the same noise sequence during combined noise experiment. π_{0jk} is the intercept, π_{mjk} is the regression slope for variable m ($m = 1, ..., M$) and e_{ijk} is the residual error term. This last term is assumed to have a mean of zero and a variance of σ_e^2 to be estimated.

Equations (6.2) and (6.3) are regression equations at individual level. Noise sensitivity is introduced to explain variation of the intercept and of the slopes; it does not vary across stimuli. Random u-terms u_{0jk} and u_{mjk} are residual errors terms at individual level. They are assumed to have a mean of zero, a variance of σ_{u0}^2 and σ_{um}^2, respectively, to be estimated and are assumed to be independent from the residual errors e_{ijk} at stimulus level. Regression coefficient β_{000}, β_{011}, β_{m00} and β_{m11} are fixed parameters: they do not vary across individuals and experiments.

A step-by-step procedure is used in order to introduce relevant parameters into the equation. First, null models (without explanatory variables at stimulus level, with and without explanatory variables at individual level) are fitted. These models will be used as a baseline for further model comparison. Then, noise indices are inserted one by one. Their slope can be either fixed or random.

Computations: Computation of multilevel regression is Bayesian and inference about the studied parameters are made using their Bayesian posterior distribution [49]. Posterior distributions of model parameters are approximated via Markov Chain Monte Carlo (MCMC) simulation, with 350,000 iterations. This simulation is performed using multilevel model fitting software MLwiN, v2.31.

Model selection: In order to select the model which enables a better calculation of annoyance ratings, three criteria are used:

- R_1^2: the proportion of variance explained at stimulus level. R_1^2 varies from 0 to 1. The closer R_1^2 is to 1, the better is the goodness-of-fit of the model to the data.
- $R_{2,m}^2$ (m=0, ..., M): the proportion of variance explained at individual level. This criterion is computed for each random coefficient at stimulus level: the intercept π_{0j} and the slope(s) π_{mj}. This criterion enables to evaluate if noise sensitivity explains variation of each random coefficient (π_{0j} or π_{mj}). $R_{2,m}^2$ varies from 0 to 1. The closer $R_{2,0}^2$ (calculated for π_{0j}) is to 1, the more noise sensitivity has an effect on individuals' mean rating. The closer $R_{2,m}^2$ (calculated for π_{mj}) is to 1, the more noise sensitivity has a moderating effect on the relationship between the m^{th} index and the annoyance ratings.
- Deviation Information Criterion (DIC): This criterion provides a measure of out-of-sample predictive error [49]. The lower the DIC is, the better is the predictive power of the model. When comparing two models, differences in DIC, of more than 10, might rule out the model with the higher DIC; differences between 5 and 10 are substantial; for a DIC difference less than 5, it could be misleading to report the model with the lower DIC [127].

N.B.: the proportion of variance explained at experiment level is not considered as neither error term nor variable is introduced at this level.

2.2.1 Multilevel regression model for urban road traffic noise annoyance

In order to contribute to annoyance modeling enhancement, several combinations of indices were selected [2], considering the combinations of indices highlighted in Chapter 4 to be relevant for urban road traffic noise annoyance and considering the verbalizations collected during combined noise experiment (*cf.* Section 2.1). Several reasons explain the choice to compute new models, in spite of using the models developed in Chapter 4. First, these previous models were develop using specific annoyance ratings. Computing new models by aggregating data of different experiments enable to consider and characterize both partial and specific annoyance ratings, as was already done in literature (*e.g.* [82]). Furthermore, aggregating data of different experiments increases noise exposure variability. Indeed, the noise sequences of the different experiments did not have neither the same duration nor the same noise level. Developed models are therefore relevant for a wider noise exposure range. Finally, the sample size is also increased, both in terms of participants and in terms of noise exposure situations, which enables robuster statistical analysis.

First, models using L_{Aeq} or N without other noise index at stimulus level, but with noise sensitivity at individual level were studied (*cf.* Table 6.5), as participants in both experiments mentioned perceived sound intensity [3]. Then, models using the indicator URA, combining loudness and different indices accounting for timbre aspect of urban road vehicle pass-by noise (*cf.* Chapter 1, Section 2.3.5.5), were studied (*cf.* Table 6.5), as participants in both experiments mentioned perceived sound intensity and timbre. Finally, as participants in both experiments mentioned also temporal features, $\sigma'(N)$ was combined with L_{Aeq}, N and URA separately (*cf.* Table 6.6). The best combinations were kept, according to DIC, R_1^2 and $R_{2,m}^2$ criteria, and including the 3 combinations of noise indices already highlighted in Chapter 4 (*cf.* Table 4.6):

- L_{Aeq} with random slope (model $L_{\text{Aeq road}}rand$),
- N with random slope (model $N_{\text{road}}rand$),
- N with moderating effect (model $N_{\text{road}}mod$),
- URA with random slope (model $URA_{\text{road}}rand$),
- URA with moderating effect (model $URA_{\text{road}}mod$),
- L_{Aeq} and $\sigma'(N)$ with random slope (model $SPD_{\text{road}}rand$ for "Sound Pressure level and loudness Derivative - Road traffic noise - random slope"),
- N and $\sigma'(N)$ with random slope (model $LD_{\text{road}}rand$ for "Loudness and its Derivative - Road traffic noise - random slope")
- and URA and $\sigma'(N)$ with fixed slope (model $URAD_{\text{road}}fix$ for "URA and loudness Derivative - Road traffic noise - fixed slope"). The indices at stimulus level are grand-mean centered. Standardized coefficients were calculated using the z-scores of all variables, in order to compare the contribution of each index to the models.

2. Null models, without (M0a) and with (M0b) noise sensitivity in the intercept, were tested. For M0a, R_1^2=0.57 and DIC=5107. For M0b, R_1^2=0.57, $R_{2,0}^2$=0.20 and DIC=5107. Noise sensitivity was therefore kept for intercept modeling and M0b was further used as a baseline.

3. When studying two-level model using L_{Aeq} without noise sensitivity and without an individual error term in the intercept, as done by Miedema and Oudshoorn [82], the slope for L_{Aeq} is not significant. L_{Aeq} alone explains therefore no variance in the annoyance ratings.

Table 6.5: Multilevel models for urban road traffic noise involving L_{Aeq} with random slope, N with random slope and with moderating effect, URA with random slope and with moderating effect. The values of L_{Aeq}, N and URA are grand mean centered with the grand-mean 56.3 dB(A), 5.67 sones and 4.74 computed across the studied stimuli. Coef. (95% CI): Coefficient and its 95% Bayesian credibility interval; [*St. Coef. (95% CI)*]: Standardized Coefficient and its 95% Bayesian credibility interval; 1st Level: Stimulus Level; 2nd Level: Individual Level. The covariances between residual errors at individual level are not shown. The answers of the 58 participants involved in the 2 experiments are used.

Model:	$L_{\text{Aeq road}}rand$	$N_{\text{road}}rand$	$N_{\text{road}}mod$	$URA_{\text{road}}rand$	$URA_{\text{road}}mod$
Index:	L_{Aeq}	N	N	URA	URA
Slope:	random slope	random slope	moderating effect	random slope	moderating effect
	Coef. (95% CI)	Coef. (95% CI)	Coef. (95% CI)	Coef. (95% CI)	Coef. (95% CI)
	[*St. Coef. (95% CI)*]	[*St. Coef. (95% CI)*]	[*St. Coef. (95% CI)*]	[*St. Coef. (95% CI)*]	[*St. Coef. (95% CI)*]
Fixed part					
β_{000} (Intercept)	1.312 (-0.674; 3.240)	3.040 (1.410; 4.638)	2.251 (0.568; 3.936)	3.421 (1.651; 5.131)	2.319 (0.381; 4.282)
β_{011} (*Sens*)	0.541 (0.242; 0.856)	0.335 (0.090; 0.587)	0.468 (0.208; 0.732)	0.310 (0.051; 0.580)	0.495 (0.199; 0.798)
	[*0.558 (0.257; 0.860)*]	[*0.347 (0.103; 0.594)*]	[*0.485 (0.220; 0.747)*]	[*0.321 (0.063; 0.583)*]	[*0.517 (0.213; 0.822)*]
β_{100} (*Index*)	0.335 (0.285; 0.385)	0.623 (0.529; 0.721)	0.351 (0.099; 0.613)	1.189 (0.998; 1.390)	0.670 (0.162; 1.200)
	[*0.966 (0.820; 1.113)*]	[*0.709 (0.601; 0.820)*]	[*0.698 (0.597; 0.806)*]	[*0.842 (0.706; 0.988)*]	[*0.827 (0.698; 0.969)*]
β_{111} ($Index \times Sens$)	–	–	0.045 (0.004; 0.087)	–	0.086 (0.004; 0.169)
	–	–	[*0.116 (0.013; 0.219)*]	–	[*0.139 (0.012; 0.268)*]
Random part					
σ_e^2 (1st Level)	1.291 (1.195; 1.394)	1.270 (1.175; 1.372)	1.271 (1.176; 1.373)	1.273 (1.177; 1.376)	1.275 (1.180; 1.378)
	[*0.277 (0.257; 0.300)*]	[*0.273 (0.253; 0.295)*]	[*0.273 (0.253; 0.295)*]	[*0.273 (0.253; 0.296)*]	[*0.274 (0.253; 0.296)*]
σ_{u0}^2 (2nd Level)	6.930 (4.747; 9.988)	5.070 (3.421; 7.342)	4.940 (3.333; 7.168)	6.758 (4.449; 9.969)	6.519 (4.309; 9.650)
	[*1.483 (1.013; 2.139)*]	[*1.086 (0.733; 1.590)*]	[*1.058 (0.717; 1.538)*]	[*1.461 (0.963; 2.173)*]	[*1.408 (0.928; 2.073)*]
σ_{u1}^2 (2nd Level)	0.030 (0.018; 0.048)	0.089 (0.046; 0.152)	0.078 (0.040; 0.137)	0.362 (0.179; 0.637)	0.319 (0.151; 0.575)
	[*0.252 (0.147; 0.395)*]	[*0.115 (0.061; 0.195)*]	[*0.102 (0.052; 0.178)*]	[*0.184 (0.093; 0.322)*]	[*0.162 (0.077; 0.293)*]
Explained variance					
R_1^2 (1st Level)	0.72	0.73	0.73	0.73	0.73
$R_{2,0}^2$ (2nd Level)	0.12	0.14	0.16	0.11	0.14
$R_{2,1}^2$ (2nd Level)	0	0	0.10	0	0.09
DIC	4529	4503	4503	4505	4506

Table 6.6: Multilevel models for urban road traffic noise involving multiple indices with random or fixed slopes. The values of L_{Aeq}, N, URA and $\sigma'(N)$ are grand mean centered with the grand-mean 56.3 dB(A), 5.67 sones, 4.74 and 33.49 sone/s computed across the studied stimuli. Coef. (95% CI): Coefficient and its 95% Bayesian credibility interval; [*St. Coef. (95% CI)*]: Standardized Coefficient and its 95% Bayesian credibility interval; 1^{st} Level: Stimulus Level; 2^{nd} Level: Individual Level. The covariances between residual errors at individual level are not shown. The answers of the 58 participants involved in the 2 experiments are used.

Model:	$SPD_{\text{road}}rand$	$LD_{\text{road}}rand$	$URAD_{\text{road}}fix$
Index:	L_{Aeq} and $\sigma'(N)$	N and $\sigma'(N)$	URA and $\sigma'(N)$
Slope:	random slope	random slope	fixed slope
	Coef. (95% CI) [*St. Coef. (95% CI)*]	Coef. (95% CI) [*St. Coef. (95% CI)*]	Coef. (95% CI) [*St. Coef. (95% CI)*]
Fixed part			
β_{000} (Intercept)	2.888 (1.116; 4.628)	3.041 (1.400; 4.690)	2.110 (0.609; 3.612)
β_{011} (*Sens*)	0.358 (0.094; 0.625)	0.336 (0.086; 0.586)	0.453 (0.219; 0.686)
	[*0.357 (0.088; 0.623)*]	[*0.337 (0.081; 0.592)*]	[*0.462 (0.226; 0.704)*]
β_{100} (L_{Aeq}, N or URA)	0.094 (0.006; 0.183)	0.392 (0.152; 0.646)	0.365 (0.117; 0.621)
	[*0.265 (0.009; 0.531)*]	[*0.433 (0.163; 0.721)*]	[*0.255 (0.075; 0.434)*]
β_{200} ($\sigma'(N)$)	0.085 (0.042; 0.127)	0.054 (0.003; 0.105)	0.079 (0.048; 0.109)
	[*0.459 (0.230; 0.683)*]	[*0.304 (0.035; 0.577)*]	[*0.425 (0.260; 0.590)*]
Random part			
σ_e^2 (1^{st} Level)	1.263 (1.166; 1.367)	1.230 (1.136; 1.332)	1.388 (1.286; 1.497)
	[*0.271 (0.251; 0.293)*]	[*0.264 (0.244; 0.286)*]	[*0.298 (0.277; 0.321)*]
σ_{u0}^2 (2^{nd} Level)	5.234 (3.521; 7.655)	5.345 (3.612; 7.804)	4.028 (2.788; 5.797)
	[*1.125 (0.752; 1.643)*]	[*1.153 (0.775; 1.678)*]	[*0.866 (0.599; 1.250)*]
σ_{u1}^2 (2^{nd} Level)	0.024 (0.009; 0.054)	0.240 (0.094; 0.506)	–
	[*0.203 (0.072; 0.446)*]	[*0.297 (0.114; 0.628)*]	–
σ_{u2}^2 (2^{nd} Level)	0.005 (0.002; 0.011)	0.007 (0.002; 0.015)	–
	[*0.147 (0.060; 0.308)*]	[*0.186 (0.064; 0.410)*]	–
Explained variance			
R_1^2 (1^{st} Level)	0.73	0.74	0.70
$R_{2,0}^2$ (2^{nd} Level)	0.14	0.13	0.18
$R_{2,1}^2$ (2^{nd} Level)	0	0	–
$R_{2,2}^2$ (2^{nd} Level)	0	0	–
DIC	4501	4474	4594

All regression coefficients were significantly different from 0. Using standardized coefficients[4], the contribution of each variable to the model can be determined. Noise sensitivity significantly contributed to the eight models (37% for $L_{\text{Aeq road}}rand$, 33% for $N_{\text{road}}rand$, 37% for $N_{\text{road}}mod$, 28% for $URA_{\text{road}}rand$, 35% for $URA_{\text{road}}mod$, 33% for $SPD_{\text{road}}rand$, 31% for $LD_{\text{road}}rand$, 40% for $URAD_{\text{road}}fix$). In particular, the interaction term (β_{111}) between noise sensitivity and N or URA contributed to the models (9% for $N_{\text{road}}mod$, 9% for $URA_{\text{road}}mod$), which increased also the contribution of noise sensitivity to the model. This highlights the relevance to consider explanatory variables at individual level in order to improve urban road traffic noise annoyance models, as a model without noise sensitivity did not enable to explain any variance of the ratings of noise annoyance (*cf.* footnote 3 of

4. The contribution of each variable to the model is calculated by dividing the corresponding standardized coefficient by the sum of all standardized coefficients.

this Chapter). These different proposed models have to be tested using *in situ* data. This will be carried out in Section 2.4.

2.2.2 Multilevel regression models for aircraft noise annoyance

Following the same rationale as in Section 2.2.1, several combinations of indices were selected [5] to characterize annoyance due to aircraft noise, considering the combinations of indices highlighted in Chapter 5 to be relevant for aircraft noise and the verbalizations collected during combined noise experiment (*cf.* Section 2.1).

First, models using L_{Aeq}, N or N_{10} without other noise index at stimulus level, but with noise sensitivity at individual level were studied (*cf.* Table 6.7), as participants in both experiments mentioned perceived sound intensity [6]. Then, models using $\sigma'(N)$ were studied (*cf.* Table 6.7), as participants in both experiments mentioned global temporal variation of aircraft noises. Finally, the indices N_{1-12} and $TETC_{13-18}$ were combined to propose a model (*cf.* Table 6.8), as participants in both experiments mentioned spectral content. The best combinations were kept, according to DIC, R_1^2 and $R_{2,m}^2$ criteria and including 4 combinations of indices highlighted in Chapter 5 (*cf.* Tables 5.4 and 5.5):

- L_{Aeq} with random slope (model $L_{\mathrm{Aeq\ air}}rand$),
- N with random slope (model $N_{\mathrm{air}}rand$),
- N_{10} with random slope (model $N_{10\ air}rand$),
- $\sigma'(N)$ with random slope (model $\sigma'(N)_{\mathrm{air}}rand$),
- $\sigma'(N)$ with moderating effect (model $\sigma'(N)_{\mathrm{air}}mod$)
- and N_{1-12} and $TETC_{13-18}$ with fixed slope (model $LMLHT_{\mathrm{air}}fix$, for "Low and Medium frequency Loudness and High frequency Tonal component - Aircraft - fixed slope").

The indices at stimulus level are grand-mean centered. Standardized coefficients were calculated using the z-scores of all variables, in order to compare the contribution of each index to the models.

5. Null models, without (M0a) and with (M0b) noise sensitivity in the intercept, were tested. For M0a, R_1^2=0.48 and DIC=4003. For M0b, R_1^2=0.48, $R_{2,0}^2$=0.15 and DIC=4003. Noise sensitivity was therefore kept for intercept modeling and M0b was further used as a baseline.

6. When studying two-level model using L_{Aeq} without noise sensitivity and without an individual error term in the intercept, as done by Miedema and Oudshoorn [82], the R_1^2 is equal to 0.12, which is the part of the variance at the first level explained by L_{Aeq}.

Table 6.7: Multilevel models for aircraft flyover noise involving L_{Aeq} with a random slope, N with a random slope, N_{10} with a random slope and $\sigma'(N)$ with a random slope and with a moderating effect. The values of L_{Aeq}, N, N_{10} and $\sigma'(N)$ are grand mean centered with the grand-mean 49.3 dB(A), 7.05 sones, 5.18 sones and 22.64 sone/s computed across the studied stimuli. Coef. (95% CI): Coefficient and its 95% Bayesian credibility interval; [*St. Coef. (95% CI)*]: Standardized Coefficient and its 95% Bayesian credibility interval; 1st Level: Stimulus Level; 2nd Level: Individual Level. The covariances between residual errors at individual level are not shown. The answers of the 59 participants involved in the 2 experiments are used.

Model:	$L_{\mathrm{Aeq\ air}}rand$	$N_{\mathrm{air}}rand$	$N_{10\ air}rand$	$\sigma'(N)_{\mathrm{air}}rand$	$\sigma'(N)_{\mathrm{air}}mod$
Index:	L_{Aeq}	N	N_{10}	$\sigma'(N)$	$\sigma'(N)$
Slope:	random slope	random slope	random effect	random slope	moderating effect
	Coef. (95% CI)	Coef. (95% CI)	Coef. (95% CI)	Coef. (95% CI)	Coef. (95% CI)
	[*St. Coef. (95% CI)*]	[*St. Coef. (95% CI)*]	[*St. Coef. (95% CI)*]	[*St. Coef. (95% CI)*]	[*St. Coef. (95% CI)*]
Fixed part					
β_{000} (Intercept)	2.032 (0.828; 3.238)	2.892 (1.489; 4.287)	3.555 (2.092; 5.056)	1.839 (0.665; 3.037)	1.525 (0.362; 2.720)
β_{011} (*Sens*)	0.304 (0.112; 0.496)	0.235 (0.019; 0.451)	0.282 (0.082; 0.480)	0.331 (0.141; 0.519)	0.387 (0.195; 0.574)
	[*0.238 (0.088; 0.390)*]	[*0.184 (0.013; 0.355)*]	[*0.221 (0.067; 0.380)*]	[*0.259 (0.112; 0.410)*]	[*0.306 (0.157; 0.455)*]
β_{100} (*Index*)	0.213 (0.178; 0.249)	0.393 (0.304; 0.498)	1.142 (0.824; 1.482)	0.157 (0.131; 0.183)	0.083 (0.010; 0.154)
	[*0.389 (0.325; 0.453)*]	[*0.583 (0.447; 0.741)*]	[*1.189 (0.868; 1.533)*]	[*0.441 (0.370; 0.512)*]	[*0.438 (0.368; 0.507)*]
β_{111} ($Index \times Sens$)	–	–	–	–	0.013 (0.001; 0.024)
	–	–	–	–	[*0.078 (0.007; 0.148)*]
Random part					
σ_e^2 (1st Level)	3.090 (2.799; 3.413)	3.087 (2.797; 3.410)	3.050 (2.756; 3.378)	3.063 (2.773; 3.383)	3.066 (2.772; 3.385)
	[*0.395 (0.357; 0.435)*]	[*0.395 (0.357; 0.435)*]	[*0.390 (0.352; 0.431)*]	[*0.391 (0.354; 0.432)*]	[*0.392 (0.355; 0.433)*]
σ_{u0}^2 (2nd Level)	3.025 (2.059; 4.411)	6.094 (4.061; 9.001)	11.628 (7.271; 17.600)	2.723 (1.836; 3.984)	2.652 (1.794; 3.872)
	[*0.387 (0.264; 0.555)*]	[*0.781 (0.519; 1.142)*]	[*1.543 (0.970; 2.320)*]	[*0.348 (0.236; 0.502)*]	[*0.339 (0.228; 0.498)*]
σ_{u1}^2 (2nd Level)	0.011 (0.006; 0.019)	0.061 (0.027; 0.119)	1.338 (0.769; 2.125)	0.006 (0.003; 0.010)	0.005 (0.003; 0.009)
	[*0.037 (0.019; 0.063)*]	[*0.136 (0.059; 0.259)*]	[*1.476 (0.860; 2.323)*]	[*0.048 (0.024; 0.081)*]	[*0.043 (0.021; 0.075)*]
Explained variance					
R_1^2 (1st Level)	0.62	0.62	0.62	0.62	0.62
$R_{2,0}^2$ (2nd Level)	0.16	0.05	0.11	0.22	0.22
$R_{2,1}^2$ (2nd Level)	0	0	0	0	0.10
DIC	3692	3689	3689	3684	3684

Table 6.8: Multilevel model for aircraft flyover noise involving multiple indices with fixed slopes. The values of N_{1-12} and $TETC_{13-18}$ are grand-mean centered with the respective grand mean 2.67 sones and 44.5 dB computed across the studied stimuli. Coef. (95% CI): Coefficient and its 95% Bayesian credibility interval; [*St. Coef. (95% CI)*]: Standardized Coefficient and its 95% Bayesian credibility interval; 1^{st} Level: Stimulus Level; 2^{nd} Level: Individual Level. The covariances between residual errors at individual level are not shown. The answers of the 59 participants involved in the 2 experiments are used.

Model:	$LMLHT_{\text{air}}fix$
Index:	N_{1-12} & $TETC_{13-18}$
Slope:	fixed slope
	Coef. (95% CI) [*St. Coef. (95% CI)*]
Fixed part	
β_{000} (Intercept)	1.431 (0.242; 2.617)
β_{011} ($Sens$)	0.401 (0.211; 0.588) [*0.317 (0.168; 0.466)*]
β_{100} (N_{1-12})	0.868 (0.593; 1.135) [*0.300 (0.204; 0.396)*]
β_{200} ($TETC_{13-18}$)	0.057 (0.033; 0.081) [*0.174 (0.100; 0.248)*]
Random part	
σ_e^2 (1^{st} Level)	3.300 (2.995; 3.630) [*0.422 (0.384; 0.465)*]
σ_{u0}^2 (2^{nd} Level)	2.696 (1.827; 3.946) [*0.345 (0.232; 0.500)*]
Explained variance	
R_1^2 (1^{st} Level)	0.59
$R_{2,0}^2$ (2^{nd} Level)	0.23
DIC	3722

All regression coefficients were significantly different from 0. Using standardized coefficients, the contribution of each variable to the model can be determined. Noise sensitivity significantly contributed to the six models (38% for $L_{\text{Aeq air}}rand$, 24% for $N_{\text{air}}rand$, 16% for $N_{10\ air}rand$, 37% for $\sigma'(N)_{\text{air}}rand$, 37% for $\sigma'(N)_{\text{air}}mod$, 51% for $LMLHT_{\text{air}}fix$). In particular, the interaction term (β_{111}) between noise sensitivity and $\sigma'(N)$ contributed to the models (9% for $\sigma'(N)_{\text{air}}mod$), which increased also the contribution of noise sensitivity to the model. Relevance to consider explanatory variables at individual level in order to enhance aircraft noise annoyance model was highlighted, as a model without individual variable explain a smaller part of the variance of the ratings of noise annoyance than the models considering an individual characteristic (*cf.* footnote 6, of this Chapter). The different proposed models have to be tested by using *in situ* data. This will be carried out in Section 2.4.

2.3 Estimation of noise indices for each respondent of the *in situ* survey

Data of the *in situ* survey in Paray-Vieille-Poste, Athis-Mons and Saint-Brice-sous-Forêt (*cf.* Chapter 2, Section 1) will be used to test noise annoyance models constructed for urban road traffic noise and for aircraft noise. In order to test these noise annoyance models with the 212 *in situ* measured partial annoyance ratings, an estimation of the values of different noise indices needs to be carried out. Indeed, the database of the *in situ* survey contains for each respondent annoyance ratings and noise exposure, only expressed in terms of L_{den} stemming from noise maps for each noise source. No other noise index is given. Therefore, an estimation of different noise indices will be performed on several *in situ* noise recordings, to obtain a relationship between a given value of L_{den} and the value of different noise indices. Then, the variation of these noise indices versus the variation of equivalent noise level will be studied to be able to estimate for each respondent the values of different noise indices.

2.3.1 Values of different noise indices from *in situ* recordings

Ninety urban road vehicle pass-by noises (30 PTWs, 30 heavy vehicles and 30 light vehicles) and 30 urban road traffic noises were randomly selected from recordings [7] carried out *in situ* in a point of the studied survey area. Different noise indices were calculated from these recordings, as well as their standard deviation (the repartition of the noise indices for different urban road noises can be approximated by a normal law). Results are given in Table 6.9.

Table 6.9: Noise indices for urban road traffic noises and urban road vehicle pass-by noises within the survey area.

	L_{Aeq}	N	$\sigma'(N)$	URA
Mean value	71.1	23.99	113.87	13.29
Standard deviation	5.5	8.44	46.15	4.43

On the basis of 12 aircraft flyover noises recorded *in situ* in some cities of the survey, different noise indices were evaluated, as well as their standard deviation (the repartition of the noise indices for the different aircraft flyover noises can be approximated by a normal law). Results are given in Table 6.10.

Table 6.10: Noise indices for aircraft flyover noises within the survey area.

	L_{Aeq}	N	N_{10}	$\sigma'(N)$	N_{1-12}	$TETC_{13-18}$
Mean value	68.1	14.83	25.78	75.52	11.58	53.7
Standard deviation	4.2	3.61	6.25	20.13	2.72	4.9

To perform noise recordings at each respondent's dwelling, to examine them and to compute for each selected noise sequence noise indices of Tables 6.9 and 6.10 was not possible, in order to know for each respondent the value of these noise indices. Therefore, a methodology to estimate them is proposed in the next section.

2.3.2 Noise index variation versus equivalent noise level variation

To be able to define respondent's noise exposure at least by noise indices approximated as a function of equivalent noise level, the variation of different noise indices with equivalent

7. These recordings were performed and provided by Bruitparif, under the supervision of C. Ribeiro, in the framework of the project related to the survey, funded by the French Ministry of Ecology (MEDDE, convention n°2100966391), in which the ENTPE was associated as partner (*cf.* [31]). The noises were recorded using an omnidirectional microphone.

noise level is evaluated by using various L_{Aeq} of noise sequences stemming from Chapters 4 and 5. This methodology was performed on the constructed noise sequences of Chapters 4 and 5 in order to get a wider range of noise situations: indeed, the *in situ* recordings were performed in only one point of the survey area. All noise recordings corresponded therefore to the same value of L_{den}, contrary to the constructed noise sequences.

Several urban road traffic noises of the experiment presented in Chapter 4 were equalized in L_{Aeq} at 7 noise levels, with a reference level $L_{Aeq\ ref}$ corresponding to the level within the experiment presented in Chapter 4, three louder noise level and three softer noise level, separated by a step of 5 dB(A). The same was done for aircraft noises of the experiment presented in Chapter 5. As experiments presented in Chapters 4 and 5 were respectively composed of 27 and 12 noise sequences, approximately a quarter of the noise sequences were selected for this step, that is to say 6 urban road traffic noises (1T3, 1T9, 1T13, 1T15, 2T5 and 2T7) and 3 aircraft flyover noises (a2, a6 and a9). These noise sequences were chosen as: 1) they were distributed along the regression line obtained between annoyance ratings and the different studied noise indices, and 2) they allow to reproduce the range of annoyance ratings observed within the experiments presented in Chapters 4 and 5. The values of the different noise indices and their variation with L_{Aeq} were computed. $TETC_{13-18}$ evolves linearly with L_{Aeq}, whereas the other noise indices (N, N_{10}, $\sigma'(N)$, N_{1-12} and URA) evolve exponentially. Coefficients of the equation of the noise indices as a function of L_{Aeq} were averaged over the 6 urban road traffic noise sequences (*cf.* Table 6.11) and over the 3 aircraft flyover noises (*cf.* Table 6.12). There was not a wide variation in the coefficients' values despite the choice of very different noise sequences, which validates the selected number of noise sequences. In Appendix C, Sections 1 and 2, the variation of each noise index with L_{Aeq} was graphically represented for an urban road traffic noise sequence and an aircraft flyover noise, respectively.

Table 6.11: Evolution of noise indices with L_{Aeq} for urban road traffic noises. $\Delta L_{\text{Aeq}} = L_{\text{Aeq}} - L_{\text{Aeq ref}}$

Evolution	N $e^{(coef \times \Delta L_{\text{Aeq}})}$	$\sigma'(N)$ $e^{(coef \times \Delta L_{\text{Aeq}})}$	URA $e^{(coef \times \Delta L_{\text{Aeq}})}$
Coefficient value	0.0747	0.0568	0.0528
Standard deviation	0.0033	0.0004	0.0020

Table 6.12: Evolution of noise indices with L_{Aeq} for aircraft flyover noises. $\Delta L_{\text{Aeq}} = L_{\text{Aeq}} - L_{\text{Aeq ref}}$

Evolution	N $e^{(coef \times \Delta L_{\text{Aeq}})}$	N_{10} $e^{(coef \times \Delta L_{\text{Aeq}})}$	$\sigma'(N)$ $e^{(coef \times \Delta L_{\text{Aeq}})}$	N_{1-12} $e^{(coef \times \Delta L_{\text{Aeq}})}$	$TETC_{13-18}$ $coef \times \Delta L_{\text{Aeq}}$
Coefficient value	0.0676	0.0647	0.0591	0.0656	0.5980
Standard deviation	0.0040	0.0036	0.0032	0.0031	0.0026

Using the evolution of the noise indices with L_{Aeq} given in Tables 6.11 and 6.12, the noise indices can be evaluated on the basis of their mean value (denoted as X_{mean}, with X the noise index) and as a function of L_{Aeq}, as following:

For urban road traffic noise:

$$N = N_{mean} \times e^{(0.0747 \times (L_{Aeq} - L_{Aeqmean}))} \quad (6.5)$$

$$\sigma'(N) = \sigma'(N)_{mean} \times e^{(0.0568 \times (L_{Aeq} - L_{Aeqmean}))} \quad (6.6)$$

$$URA = URA_{mean} \times e^{(0.0528 \times (L_{Aeq} - L_{Aeqmean}))} \quad (6.7)$$

For aircraft noise:

$$N = N_{mean} \times e^{(0.0676 \times (L_{Aeq} - L_{Aeqmean}))} \quad (6.8)$$

$$N_{10} = N_{10mean} \times e^{(0.0647 \times (L_{Aeq} - L_{Aeqmean}))} \quad (6.9)$$

$$\sigma'(N) = \sigma'(N)_{mean} \times e^{(0.0591 \times (L_{Aeq} - L_{Aeqmean}))} \quad (6.10)$$

$$N_{1-12} = N_{1-12mean} \times e^{(0.0656 \times (L_{Aeq} - L_{Aeqmean}))} \quad (6.11)$$

$$TETC_{13-18} = TETC_{13-18mean} + 0.5980 \times (L_{Aeq} - L_{Aeqmean}) \quad (6.12)$$

N.B.: These estimations of loudness as a function of L_{Aeq} are compared with the well-known equation of Stevens [122] in Appendix D.

To estimate the value of the indices for each respondent, noise level the respondent were exposed to will be estimated using L_{den} from noise maps. In the equations 6.5 to 6.12, L_{Aeq} will therefore be replaced by L_{den}, which is constructed from L_{Aeq}. This is an approximation. Replacement of L_{Aeq} by L_{den} in models was already done in literature for models initially developed with L_{Aeq} (*e.g.* [95, 105, 106]). Using the mean values estimated from the *in situ* recordings (*cf.* Tables 6.9 and 6.10), the indices for each respondent of the survey can be estimated using the following equations:

For urban road traffic noise:

$$N = 23.99 \times e^{(0.0747 \times (L_{den} - 71.1))} \quad (6.13)$$

$$\sigma'(N) = 113.87 \times e^{(0.0568 \times (L_{den} - 71.1))} \quad (6.14)$$

$$URA = 13.29 \times e^{(0.0528 \times (L_{den} - 71.1))} \quad (6.15)$$

For aircraft noise:

$$N = 14.83 \times e^{(0.0676 \times (L_{den} - 68.1))} \quad (6.16)$$

$$N_{10} = 25.78 \times e^{(0.0647 \times (L_{den} - 68.1))} \quad (6.17)$$

$$\sigma'(N) = 75.52 \times e^{(0.0591 \times (L_{den} - 68.1))} \quad (6.18)$$

$$N_{1-12} = 11.58 \times e^{(0.0656 \times (L_{den} - 68.1))} \quad (6.19)$$

$$TETC_{13-18} = 53.7 + 0.5980 \times (L_{den} - 68.1) \quad (6.20)$$

2.4 Testing of noise annoyance models with *in situ* measured partial annoyance ratings

Using equations 6.13 to 6.20, different noise indices and therefore different annoyance models can be estimated for each respondent (denoted as i in subscript) of the survey and compared to measured partial annoyance ratings. Models (for road traffic noise, *cf.* Tables 6.5 and 6.6 and for aircraft noise, *cf.* Tables 6.7 and 6.8) were tested, as done by Miedema [81] and Klein [60], using only fixed parameters of multilevel models (*i.e.* β_{000}, β_{011}, β_{m00} and β_{m11} for the models proposed in Sections 2.2.1 and 2.2.2). The models are therefore used in a simpler form, with the grand-mean value (denoted as $Index_{m\ Grand\ Mean}$) for each index m, as follows:

$$A_i = \pi_{0i} + \sum_{m=1}^{M} \pi_{mi}(Index_{mi} - Index_{m\ Grand\ Mean}) \tag{6.21}$$

$$\pi_{0i} = \beta_{000} + \beta_{011} \times Sens_i \tag{6.22}$$

$$\pi_{mi} = \beta_{m00} + \beta_{m11} \times Sens_i \tag{6.23}$$

Previously constructed annoyance models were tested comparing predicted annoyance with individual partial annoyance ratings measured *in situ* for road traffic noise (*cf.* Table 6.13) and for aircraft noise (*cf.* Table 6.14). Three parameters (r, intercept and slope) are used to test partial annoyance models: they result from correlation and regression analysis between measured partial annoyance and corresponding calculated partial annoyance, obtained using the values of independent variables in regression equations obtained for each model. These 3 parameters are used to assess the quality of partial annoyance models (underestimation or overestimation). A perfect prediction by a model would lead to (r, intercept, slope) = (1, 0, 1), *i.e.* all dots would be perfectly lined up on the bisector of the plan. This comparison enables to evaluate both the models, developed in Sections 2.2.1 and 2.2.2, and the estimation of the values of the noise indices using L_{den} values, performed in Section 2.3.

Table 6.13: Predicted partial annoyance compared to 212 individual partial annoyance ratings for road traffic noise of the *in situ* survey. ^{a}: p≤0.05 (written also in red).

Model	intercept	slope	r
$L_{\text{Aeq road}}rand$ [4]	3.05^a	0.41^a	0.45^a
$N_{\text{road}}rand$	5.64^a	0.40^a	0.32^a
$N_{\text{road}}mod$	4.83^a	0.54^a	0.39^a
$URA_{\text{road}}rand$	6.11^a	0.36^a	0.33^a
$URA_{\text{road}}mod$	5.13^a	0.54^a	0.42^a
$SPD_{\text{road}}rand$	6.10^a	0.20^a	0.25^a
$LD_{\text{road}}rand$	6.39^a	0.30^a	0.32^a
$URAD_{\text{road}}fix$	5.99^a	0.27^a	0.31^a

Table 6.14: Predicted partial annoyance compared to 212 individual partial annoyance ratings for aircraft noise of the *in situ* survey. ^{a}: p≤0.05 (written also in red).

Model	intercept	slope	r
$L_{\text{Aeq air}}rand$ [4]	1.54^a	0.28^a	0.51^a
$N_{\text{air}}rand$	1.96^a	0.17^a	0.50^a
$N_{10\ air}rand$	3.99^a	0.49^a	0.47^a
$\sigma'(N)_{\text{air}}rand$	1.99^a	0.29^a	0.51^a
$\sigma'(N)_{\text{air}}mod$	1.96^a	0.30^a	0.52^a
$LMLHT_{\text{air}}fix$	1.99^a	0.31^a	0.51^a

4. As done before, L_{Aeq} was replaced by L_{den}.

For road traffic noise (*cf.* Table 6.13), models can be divided into three significantly different groups: i) $L_{\text{Aeq road}}rand$ and $URA_{\text{road}}mod$ (0.42≤r≤0.45), ii) $N_{road}mod$ (r=0.39) and iii) the other models (0.25≤r≤0.33). For aircraft flyover noise (*cf.* Table 6.14), the different models provided similar prediction of the partial annoyance ratings (0.47≤r≤0.52). All these models were better correlated with measured partial annoyance ratings than did L_{den} index used in a simple linear regression (r=0.22, p<0.05 for road traffic noise; r=0.39, p<0.05 for aircraft noise). This result highlights that the models and the estimation of the noise indices for each respondent of the *in situ* survey enable to better predict measured partial noise annoyance ratings than L_{den} index.

In the following, for road traffic noise, only $L_{\text{Aeq road}}rand$ and $URA_{\text{road}}mod$ will be kept, as these models are the ones better correlated with *in situ* annoyance ratings. The model $L_{Aeq\ road}rand$ is very simple (no need to estimate an index) and the model $URA_{\text{road}}mod$ enables to characterize different annoying acoustical features of road traffic noise (perceived noise intensity, spectral content and modulation-related sensations). For aircraft noise, as the different models are similar in terms of quality of prediction, only models with the highest correlation with *in situ* measured partial annoyances will be used in the following. The kept models are $L_{\text{Aeq air}}rand$ (for the same reason as for the road traffic noise) and $\sigma'(N)_{\text{air}}mod$, as this model enables to characterize a different annoying acoustical feature: global temporal variations. The model $LMLHT_{\text{air}}fix$ was not kept, in spite of characterizing spectral content, as two noise indices have to be estimated.

2.5 Total noise annoyance studied under laboratory conditions

Combined noise experiment data were used to construct total noise annoyance models. First, the phenomena of the combination of noises were studied, using analysis of variance with repeated measures (RM ANOVA) and Vos' representation. Then, total annoyance models from literature were constructed using the data of the experiment.

2.5.1 Analysis of variance

Stimuli of combined noise experiment were constructed on the basis of two factors: "URTN" for urban road traffic noise and "AN" for aircraft noise. The effects of these factors on partial annoyance due to urban road traffic noise, on partial annoyance due to aircraft noise and on total noise annoyance will be studied using a two-factorial RM ANOVA, with four levels per factor.

2.5.1.1 Partial annoyance due to urban road traffic noise

The two main factors URTN and AN had a significant effect on urban road traffic noise annoyance (respectively, [F(3, 93)=75.59; p<0.05, ϵ=1] and [F(3, 93)=7.66; p<0.05, ϵ=0.92]). Proportion of variance explained (η^2) by the factor URTN was moderate, i.e. 26%, and the one explained by the factor AN was very small, i.e. 3%. The interaction between the factors URTN × AN had no effect on urban road traffic partial annoyance ([F(9, 279)=1.72; p>0.05, ϵ=0.85]).

2.5.1.2 Partial annoyance due to aircraft noise

Only the main factor AN had a significant effect on aircraft noise annoyance ([F(3, 93)=40.55; $p<0.05$, ϵ=0.84]). Proportion of variance explained (η^2) by the factor AN was moderate, i.e. 28%. Both the main factor URTN and the interaction between the factors URTN × AN had no effect on the aircraft partial annoyance (respectively, [F(3, 93)=1.73; $p>0.05$, ϵ=1] and [F(9, 279)=0.79; $p>0.05$, ϵ=0.78]).

2.5.1.3 Total annoyance

The two main factors URTN and AN had a significant effect on total noise annoyance (respectively, [F(3, 93)=20.34; $p<0.05$, ϵ=1] and [F(3, 93)=15.38; $p<0.05$, ϵ=1]). Proportion of variance explained (η^2) by the factor URTN was moderate, i.e. 15%, but higher than the proportion of variance explained by the factor AN, i.e. 8%, indicating that urban road traffic noise sequences influenced total annoyance more than aircraft noise sequences did. The interaction between the factors URTN × AN had no effect on total annoyance ([F(9, 279)=1.72; $p>0.05$, ϵ=0.85]).

2.5.2 Vos' representations carried out on annoyance rated in laboratory conditions

Vos' representations [136] were drawn to investigate potential interaction effects between combined noises on total annoyance (*cf.* Figure 6.2 and in Appendix E). On this kind of representation, one noise source exposure is fixed, whereas the second one varies. Both partial annoyances and total annoyance are represented as a function of the varying noise source: partial annoyance of the fixed noise source is therefore represented as an horizontal line.

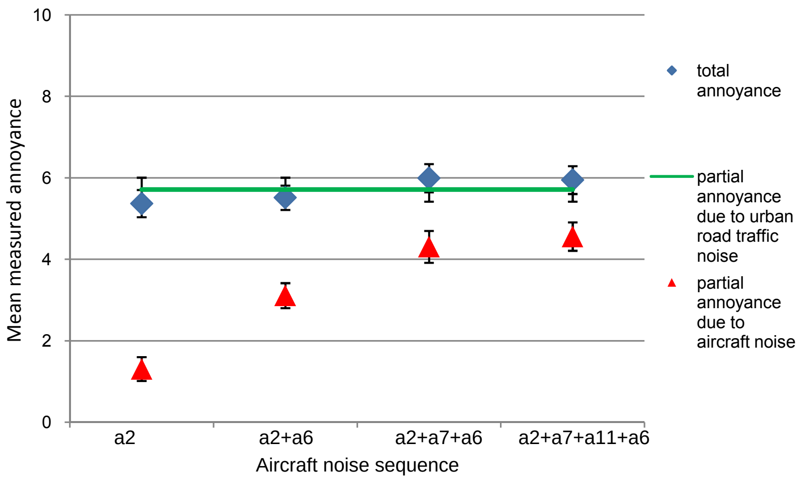

Figure 6.2: Vos' representation for the fixed road traffic noise sequence 2T11 and varying aircraft noise sequences. ♦: Mean measured total annoyance due to URTN(2T11)+AN(X), as a function of the aircraft noise sequence; ▲: Mean measured partial annoyance due to aircraft noise; —: Mean measured partial annoyance due to urban road traffic noise sequence 2T11. The error bars represent the standard errors.

On the 16 studied combined noise situations, according to t-tests, total annoyance was not significantly different from the maximum specific annoyance for 13 situations: a strongest component phenomenon was observed. Strongest component total annoyance model should therefore be evaluated. For 2 other situations, total annoyance was significantly higher than the highest specific annoyance: some synergistic effects occur.

2.5.3 Combined noise annoyance models calculated using laboratory data

Considering the results of RM ANOVA (*cf.* Section 2.5.1.3) and of Vos' representation (*cf.* Figure 6.2), different total annoyance models, described and previously discussed in literature (*cf.* Chapter 1, Section 3.3), were adjusted using mean measured total annoyance ratings:

- psychophysical models:
  - energy summation model (*cf.* Chapter 1, Section 3.3.1);
  - independent model (*cf.* Chapter 1, Section 3.3.3);
  - energy difference model (*cf.* Chapter 1, Section 3.3.4);
  - mixed model (*cf.* Chapter 1, Section 3.3.7);
  - weighted summation model (*cf.* Chapter 1, Section 3.3.5);
  - annoyance equivalents model (*cf.* Chapter 1, Section 3.3.5);
- perceptual models:
  - linear regression model (*cf.* Chapter 1, Section 3.3.8);
  - mixed model (*cf.* Chapter 1, Section 3.3.7);
  - strongest component model (*cf.* Chapter 1, Section 3.3.2);
  - vector summation model (*cf.* Chapter 1, Section 3.3.6).

Concerning psychophysical models (*cf.* Table 6.15), they used L_{Aeq} values and also N values, as proposed in [91]. Concerning perceptual models (*cf.* Table 6.17), they were evaluated using mean measured partial annoyance ratings and also mean calculated partial annoyance ratings, using selected annoyance models (*cf.* Sections 2.2.1, 2.2.2 and 2.4).

Four parameters are used to compare total annoyance models:

- R^2_{adj}: it results from linear regression analysis carried out between mean measured total annoyance responses and the L_{Aeq} or N values. The higher R^2_{adj}, the better the goodness of fit;
- r, intercept and slope: they result from correlation and regression analysis between mean measured total annoyance ratings and calculated total annoyance ratings (denoted A_T), obtained using values of the independent variables in regression equations of each model. These 3 parameters are used to assess the quality of total annoyance models (underestimation or overestimation). A perfect calculation by a model would lead to (r, intercept, slope) = (1, 0, 1), i.e. all dots would be perfectly lined up on the bisector of the plan.

Considering Table 6.15, several psychophysical models should be kept for further modeling and tested using *in situ* survey data: i) considering L_{Aeq} as a variable, energy summation, independent effect and weighted summation models, and ii) considering N as a variable, energy summation, independent effect and energy difference models. The other models were not kept as one of their coefficients was not significantly different from 0 and as they did not allow enhancement compared to the ones with significant coefficients (*e.g.* energy difference model compared to energy summation model by considering L_{Aeq} as a variable).

Considering Tables 6.16 and 6.17, several perceptual models should be kept for further modeling and tested using *in situ* survey data: i) considering measured partial annoyance ratings as variables, linear regression, strongest component and vector summation models and ii) considering partial annoyance ratings calculated by models $L_{\mathrm{Aeq\ road}}rand$ or $URA_{\mathrm{road}}mod$ for road traffic noise (*cf.* Table 6.5) and $\sigma'(N)_{\mathrm{air}}mod$ or $L_{\mathrm{Aeq\ air}}rand$, for aircraft noise (*cf.* Table 6.7) as variables, the linear regression model. The other models were not kept as one of their coefficients was not significantly different from 0 or as they did not enable a good calculation of total annoyance rating.

Considering R^2_{adj} values, it seems that linear regression and vector summation models with measured partial annoyance ratings enabled the better calculation of total annoyance ratings (R^2_{adj} higher than 0.90).

Table 6.15: Psychophysical total annoyance models constructed using the data of combined noise experiment. [a]: p≤0.05 (written also in red). Relevant equations with standardized coefficients are given between brackets. The answers of the 32 participants are used.

Model	Index	Equation	R^2_{adj}	intercept	slope	r
Energy summation		$A_T = -10.75^a + 0.31^a \times L_T$	0.86^a	0.65	0.87^a	0.93^a
Independent effect		$A_T = -8.02^a + 0.22^a \times L_{\text{road}} + 0.05^a \times L_{\text{aircraft}}$	0.74^a	1.20^a	0.79^a	0.88^a
		$(A_T = 0.77^a \times L_{\text{road}} + 0.42^a \times L_{\text{aircraft}})$				
Energy difference		$A_T = -10.21^a + 0.30^a \times L_T - 0.01 \times \lvert L_{\text{road}} - L_{\text{aircraft}}\rvert$	0.85^a	0.62	0.87^a	0.93^a
Mixed		$A_T = -8.06^a + 0.22^a \times L_{\text{road}} + 0.05 \times L_{\text{aircraft}} + 0.00 \times \lvert L_{\text{road}} - L_{\text{aircraft}}\rvert$	0.72^a	1.18	0.79^a	0.88^a
Weighted summation	L_{Aeq}	$A_{\text{road}} = -8.40^a + 0.27^a \times L_{\text{road}}$ (R^2_{adj}=0.97^a); $A_{\text{aircraft}} = -6.03^a + 0.19^a \times L_{\text{aircraft}}$ (R^2_{adj}=0.74^a)				
		$P_{\text{aircraft}} = \frac{2.37-0.08\times L_{\text{aircraft}}}{0.27}$				
		k=10 $A_T = -10.08^a + 0.30^a \times L_t$	0.74^a	1.19	0.75^a	0.87^a
		k=15 $A_T = -10.59^a + 0.30^a \times L_t$	0.76^a	0.99	0.76^a	0.88^a
Energy summation		$A_T = 2.30^a + 0.79^a \times N_T$[5]	0.82^a	0.83	0.83^a	0.91^a
Independent effect		$A_T = 2.41^a + 0.66^a \times N_{\text{road}} + 0.07^a \times N_{\text{aircraft}}$	0.76^a	1.00	0.80^a	0.89^a
		$(A_T = 0.77^a \times N_{\text{road}} + 0.45^a \times N_{\text{aircraft}})$				
Energy difference	N	$A_T = 2.04^a + 0.76^a \times N_T + 0.05^a \times \lvert N_{\text{road}} - N_{\text{aircraft}}\rvert$	0.87^a	0.57	0.88^a	0.94^a
		$(A_T = 0.88^a \times N_T + 0.23^a \times \lvert N_{\text{road}} - N_{\text{aircraft}}\rvert)$				
Mixed		$A_T = 2.09^a + 0.72^a \times N_{\text{road}} - 0.01 \times N_{\text{aircraft}} + 0.12 \times \lvert N_{\text{road}} - N_{\text{aircraft}}\rvert$	0.76^a	0.95	0.81^a	0.90^a

Table 6.16: Perceptual total annoyance models constructed using measured partial annoyance of combined noise experiment. [a]: p≤0.05 (written also in red). Relevant equations with standardized coefficients are given between brackets. The answers of the 32 participants are used.

Model	Index	Equation	R^2_{adj}	intercept	slope	r
Linear regression		$A_T = 0.19 + 0.29^a * A_{\text{aircraft}} + 0.80^a * A_{\text{road}}$	0.90^a	0.44	0.91^a	0.95^a
		$(A_T = 0.54^a * A_{\text{aircraft}} + 0.78^a * A_{\text{road}})$				
Mixed	A_{aircraft}	$A_T = -0.04 + 0.47^a * A_{\text{aircraft}} + 0.65^a * A_{\text{road}}$	0.90^a	0.40	0.92^a	0.96^a
	&	$+0.21 \times \lvert A_{\text{aircraft}} - A_{\text{road}}\rvert$				
	A_{road}	$(A_T = 0.90^a * A_{\text{aircraft}} + 0.63^a * A_{\text{road}} + 0.39 \times \lvert A_{\text{aircraft}} - A_{\text{road}}\rvert)$				
Strongest component		$A_T = max(A_{\text{aircraft}}; A_{\text{road}})$	0.68^a	1.10	0.75^a	0.84^a
Vector summation		$A_T = \sqrt{A^2_{\text{aircraft}} + A^2_{\text{road}} + 2 \times A_{\text{aircraft}} \times A_{\text{road}} \times cos(1.92rad)}$	0.93^a	0.53	0.89^a	0.97^a

5. N_T was directly measured on combined noise sequences.

Table 6.17: Perceptual total annoyance models constructed using calculated partial annoyance of combined noise experiment. [a]: p≤0.05 (written also in red). Relevant equations with standardized coefficients are given between brackets. The answers of the 32 participants are used.

Model	Index	Equation	R^2_{adj}	intercept	slope	r
Linear regression		$A_T = 2.66^a + 0.25^a * \sigma'(N)_{\text{air}}mod + 0.65^a * L_{Aeq\ road}rand$	0.75^a	1.01	0.78^a	0.89^a
		$(A_T = 0.43^a * \sigma'(N)_{\text{air}}mod + 0.77^a * L_{Aeq\ road}rand)$				
Mixed	$\sigma'(N)_{\text{air}}mod$	$A_T = 2.53^a + 0.22^a * \sigma'(N)_{\text{air}}mod + 0.70^a * L_{Aeq\ road}rand$	0.74^a	1.03	0.79^a	0.89^a
	&	$+0.09 \times \lvert\sigma'(N)_{\text{air}}mod - L_{Aeq\ road}rand\rvert$				
Strongest component	$L_{Aeq\ road}rand$	$A_T = max(\sigma'(N)_{\text{air}}mod; L_{Aeq\ road}rand)$	0.29^a	-0.15	0.76^a	0.58^a
Vector summation		$A_T = (\sigma'(N)_{\text{air}}mod^2 + L_{Aeq\ road}rand^2$	0.56^a	-1.71	1.29^a	0.77^a
		$+ 2 \times \sigma'(N)_{\text{air}}mod \times L_{Aeq\ road}rand \times cos(1.26rad))^{1/2}$				
Linear regression		$A_T = 0.32 + 0.25^a * \sigma'(N)_{\text{air}}mod + 1.13^a * URA_{\text{road}}mod$	0.70^a	1.26^a	0.74^a	0.86^a
		$(A_T = 0.43^a * \sigma'(N)_{\text{air}}mod + 0.75^a * URA_{\text{road}}mod)$				
Mixed	$\sigma'(N)_{\text{air}}mod$	$A_T = 0.17 + 0.27 * \sigma'(N)_{\text{air}}mod + 1.15^a * URA_{\text{road}}mod$	0.68^a	1.26^a	0.74^a	0.86^a
	&	$+0.04 \times \lvert\sigma'(N)_{\text{air}}mod - URA_{\text{road}}mod\rvert$				
Strongest component	$URA_{\text{road}}mod$	$A_T = max(\sigma'(N)_{\text{air}}mod; URA_{\text{road}}mod)$	0.29^a	2.18^a	0.34^a	0.58^a
Vector summation		$A_T = (\sigma'(N)_{\text{air}}mod^2 + URA_{\text{road}}rand^2$	0.43^a	0.80	0.95^a	0.69^a
		$+ 2 \times \sigma'(N)_{\text{air}}mod \times URA_{\text{road}}rand \times cos(1.41rad))^{1/2}$				
Linear regression		$A_T = 1.52^a + 0.23^a * L_{\text{Aeq air}}rand + 0.65^a * L_{\text{Aeq road}}rand$	0.74^a	1.08	0.78^a	0.88^a
		$(A_T = 0.42^a * L_{\text{Aeq air}}rand + 0.77^a * L_{\text{Aeq road}}rand)$				
Mixed	$L_{\text{Aeq air}}rand$	$A_T = 1.52^a + 0.23^a * L_{\text{Aeq air}}rand + 0.65^a * L_{\text{Aeq road}}rand$	0.74^a	1.08	0.78^a	0.88^a
	&	$+0.00 \times \lvert L_{\text{Aeq air}}rand - L_{\text{Aeq road}}rand\rvert$				
Strongest component	$L_{\text{Aeq road}}rand$	$A_T = max(L_{\text{Aeq air}}rand; L_{\text{Aeq road}}rand)$	0.12	–	–	–
Vector summation		$A_T = (L_{\text{Aeq air}}rand^2 + L_{\text{Aeq road}}rand^2$	-0.07	–	–	–
		$+ 2 \times L_{\text{Aeq air}}rand \times L_{\text{Aeq road}}rand \times cos(2.58rad))^{1/2}$				
Linear regression		$A_T = -0.82 + 0.23^a * L_{\text{Aeq air}}rand + 1.13^a * URA_{\text{road}}mod$	0.70^a	1.27^a	0.74^a	0.86^a
		$(A_T = 0.42^a * L_{\text{Aeq air}}rand + 0.75^a * URA_{\text{road}}mod)$				
Mixed	$L_{\text{Aeq air}}rand$	$A_T = -0.82 + 0.23^a * L_{\text{Aeq air}}rand + 1.13^a * URA_{\text{road}}mod$	0.70^a	1.27^a	0.74^a	0.86^a
	&	$+0.00 \times \lvert L_{\text{Aeq air}}rand - URA_{\text{road}}mod\rvert$				
Strongest component	$URA_{\text{road}}mod$	$A_T = max(L_{\text{Aeq air}}rand; URA_{\text{road}}mod)$	0.12	–	–	–
Vector summation		$A_T = (L_{\text{Aeq air}}rand^2 + URA_{\text{road}}mod^2$	-0.02	–	–	–
		$+ 2 \times L_{\text{Aeq air}}rand \times URA_{\text{road}}mod \times cos(2.58rad))^{1/2}$				

2.6 Total noise annoyance models tested using *in situ* survey data

Total noise annoyance ratings collected *in situ* during the survey were used to studied perceptual phenomena due to the combination of noises, using Vos' representation. Then, previously constructed total annoyance models were tested using data of the survey.

2.6.1 Vos' representation carried out on annoyance measured *in situ*

Partial and total annoyance ratings were averaged over respondents exposed to a range of 5 dB(A) of L_{den} for each noise source, in accordance with the European directive 2002/49/EC [70]. Sample of these categories of single and combined noise exposure are given in Table 6.18. In order to calculate mean partial and total annoyance ratings and considering Table 6.18, only categories with more than 20 respondents for single exposure and categories with more than 10 respondents for combined exposure were considered, as a compromise between: i) the classical cutoff value of 30 respondents (*cf.* [118]) and ii) the restricted sample size of the *in situ* survey, distributed over numerous categories of noise exposure. From these criteria and Table 6.18, five categories of combined noise exposure (written in red in the Table 6.18) were therefore considered in the following.

Table 6.18: L_{den} categories for exposure to single and combined noises and corresponding sample size. Retained sample sizes are written in red.

Sample size		Aircraft noise $40 \leq L_{den} < 45$	Aircraft noise $50 \leq L_{den} < 55$	Total
Road traffic noise	$L_{den} < 50$	1	–	1
	$50 \leq L_{den} < 55$	46	5	51
	$55 \leq L_{den} < 60$	78	22	100
	$60 \leq L_{den} < 65$	13	26	39
	$65 \leq L_{den} < 70$	12	6	18
	$70 \leq L_{den} < 75$	1	–	1
	$75 \leq L_{den}$	2	–	2
Total		153	59	

Two Vos' representations were therefore drawn (one per column of Table 6.18): one with 3 mean total annoyance ratings (*cf.* Figure 6.3) and one with 2 mean total annoyance ratings (*cf.* Figure 6.4). On both figures, it appears that total annoyance was not significantly different from the maximum specific annoyance. Strongest component model should therefore enable a good prediction of the results.

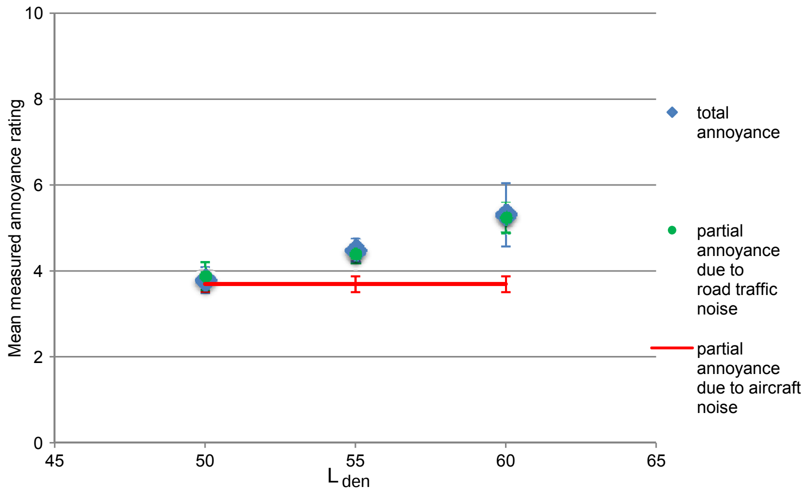

Figure 6.3: Vos' representation for aircraft noise L_{den} fixed between 40 and 45 dB(A) and varying road traffic noise L_{den}. ♦: Mean measured total annoyance due to aircraft noise L_{den} ranging from 40 to 45 dB(A), as a function of road traffic noise L_{den}; —: Mean measured partial annoyance due to aircraft noise L_{den} ranging from 40 to 45 dB(A); •: Mean measured partial annoyance due to varying road traffic noise L_{den}. The error bars represent the standard errors.

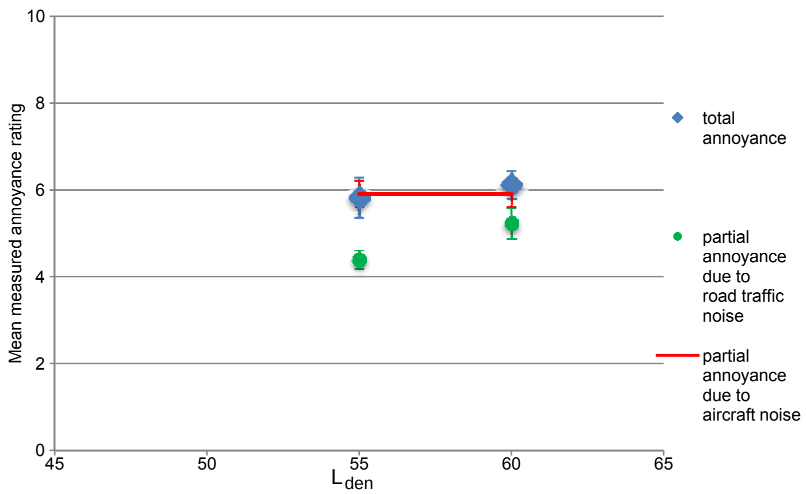

Figure 6.4: Vos' representation for aircraft noise L_{den} fixed between 50 and 55 dB(A) and varying road traffic noise L_{den}. ♦: Mean measured total annoyance due to aircraft noise L_{den} ranging from 50 to 55 dB(A), as a function of road traffic noise L_{den}; —: Mean measured partial annoyance due to aircraft noise L_{den} ranging from 50 to 55 dB(A); •: Mean measured partial annoyance due to varying road traffic noise L_{den}. The error bars represent the standard errors.

2.6.2 Testing of constructed total annoyance models using individual *in situ* total annoyance ratings

Previously constructed total annoyance models (*cf.* Tables 6.15, 6.16, 6.17) were tested using individual *in situ* total annoyance ratings (*cf.* Table 6.19). Noise indices used in total annoyance models to consider *in situ* exposure to road traffic and aircraft noises (*i.e.* N, $\sigma'(N)$ and URA) were estimated following the methodology presented in Section 2.3.2. For each noise source, L_{Aeq} in models is replaced by the L_{den} value of the survey. Energy summation and energy difference models based on loudness were not tested, as total loudness of *in situ* combined noises can not be evaluated.

Table 6.19: Total annoyance models tested using 212 individual total annoyance ratings of the *in situ* survey. [a]: $p \leq 0.05$ (written also in red). r, intercept and slope: they result from correlation and regression analysis between measured total annoyance responses and the predicted ones.

Model	Index	intercept	slope	r
Energy summation	L_{den}	6.23[a]	0.10[a]	0.18[a]
Independent effect	L_{den}	6.60[a]	0.09[a]	0.20[a]
Weighted summation k=10	L_{den}	7.01[a]	0.09[a]	0.16[a]
Weighted summation k=15	L_{den}	7.11[a]	0.09[a]	0.17[a]
Independent effect	N	8.41[a]	0.15	0.12
Linear regression	A_{aircraft} & A_{road}	1.10[a]	0.82[a]	0.85[a]
Strongest component	A_{aircraft} & A_{road}	1.19[a]	0.84[a]	0.87[a]
Vector summation	A_{aircraft} & A_{road}	1.12[a]	0.89[a]	0.89[a]
Linear regression	$\sigma'(N)_{\text{air}}mod$ & $L_{\text{Aeq road}}rand$	5.07[a]	0.33[a]	0.48[a]
Linear regression	$\sigma'(N)_{\text{air}}mod$ & $URA_{\text{road}}mod$	6.68[a]	0.62[a]	0.41[a]
Linear regression	$L_{\text{Aeq air}}rand$ & $L_{\text{Aeq road}}rand$	3.80[a]	0.32[a]	0.47[a]
Linear regression	$L_{\text{Aeq air}}rand$ & $URA_{\text{road}}mod$	5.41[a]	0.60[a]	0.41[a]

Total annoyance predicted from the independent effect model using loudness is not correlated with measured total annoyance. The perceptual total annoyance models provided a better prediction of individual total annoyance ratings than the other psychophysical models. As expected, perceptual total annoyance models based on measured partial annoyance ratings provided an even better prediction of total annoyance ratings than the ones based on predicted partial annoyance ratings. In particular, the linear regression model using the variable $A_{road\ partial}$ predicted using $L_{\text{Aeq road}}rand$ and the variable $A_{air\ partial}$ predicted using $L_{\text{Aeq air}}rand$, *i.e.* the perceptual model using partial annoyance predicted from both L_{den} and noise sensitivity, provided a better prediction of individual total annoyance ratings (r=0.47) than the independent effect model, a psychophysical model using the variable L_{den} of each noise source (r=0.20). These results show that total annoyance models based on partial annoyance models (considering individual noise sensitivity) associated to the estimation of the values of noise indices enabled a better prediction of *in situ* total annoyance ratings than total annoyance models only based on L_{den} index. This highlights that it is still necessary to improve physical and perceptual characterization of single noise exposure. This effort would also benefit to the prediction of individual total annoyance.

3 Discussion

Noise annoyance due to urban road traffic noise, due to aircraft noise and to these combined noises was studied using laboratory and *in situ* data. The main objectives were: i) to identify acoustical features influencing partial annoyance and to compare them with identified influential acoustical features for specific annoyance, ii) to propose relevant annoyance models considering both acoustical indices and noise sensitivity for single exposure using laboratory data, iii) to test these models with *in situ* data, iv) to study combined effects when urban traffic noise and aircraft noise are combined, v) to propose total noise annoyance models for this type of combined noise exposure using laboratory data, and vi) to test these total noise annoyance models with *in situ* data.

Verbalization task of combined noise experiment enabled to highlight three main acoustical features for urban road traffic noise and for aircraft noise: i) global temporal variation, ii) perceived noise intensity and iii) timbre (*cf.* Table 6.4). These acoustical features are similar to the ones observed in the previous single noise experiments (*cf.* Chapters 4 and 5). The previously highlighted indices can therefore be kept to be used in annoyance models for urban road traffic noise and for aircraft noise.

Multilevel regressions were performed in order to build annoyance models, considering both noise indices and noise sensitivity. Furthermore, data from single noise experiments and from combined noise experiments were aggregated using such opportunity given by multilevel regression. Several reasons justify the choice to aggregate data from different experiments:

- Multilevel regression enables to consider experiment as a level of the equation. This mathematical model is appropriate to consider the structure of the data.
- For the construction of dose-effect relationships, Miedema and Oudshoorn [82] used data from several surveys, carried out in different countries, for different combined noise sources, studied in different years, with different questionnaires, with different annoyance scales and different *in situ* noise exposure characterization. The data from our different experiments carried out under laboratory conditions are obtained with similar ranges of incertitude (*e.g.* for annoyance measurement, the scale used in the 3 experiments was the same).
- Previously, in Chapters 4 and 5, annoyance models were built on specific annoyance, whereas partial annoyance was measured during combined noise experiment. Aggregating data from the different experiments enable to consider both specific and partial annoyances due to urban road traffic or aircraft noise in the construction of annoyance models, as was already done by Miedema and Oudshoorn [82].

Combinations of noise indices highlighted in Chapters 4 and 5 were introduced in multilevel regression, resulting in 8 urban road traffic noise annoyance models (*cf.* Tables 6.5 and 6.6) and in 6 aircraft noise annoyance models (*cf.* Tables 6.7 and 6.8). Even though different annoyance ratings (*e.g.* specific and partial annoyances) and different noise situations (*e.g.* single and combined noise exposures) were considered, the combinations of indices highlighted in Chapters 4 and 5 for specific annoyance ratings remained relevant for combined noise exposure. These models for both specific and partial annoyances led to comparable goodness-of-fit and out-of-sample predictive errors. Noise sensitivity highly contributed in all models, confirming the results of Chapters 2, 4 and 5 and the findings of literature (*e.g.* [117, 130, 131, 133]). Some models highlighted a significant moderating effect of noise sensitivity on the relationship between noise indices and noise annoyance

($N_{\text{road}}mod$, $URA_{\text{road}}mod$ and $\sigma'(N)_{\text{road}}mod$). Some authors also found a moderating effect (*e.g.* [84, 99]) whereas some authors did not observe such effect (*e.g.* [117, 130, 131, 133]). This may be explained by the fact that this effect is weak when significant. The influence of noise sensitivity on annoyance militates therefore to build new exposure-response relationships considering this factor, as proposed by Gille *et al.* [42].

Partial annoyance models were tested using *in situ* measured partial annoyances due to urban road traffic noise and to aircraft noise. For both noise sources, Miedema and Oudshoorn's model based on L_{den} [82] underestimated measured partial annoyance (*cf.* Figure 1.5). For road traffic noise (*cf.* Table 6.13), two models were better correlated with noise annoyance than the others: $L_{\text{Aeq road}}rand$ and $URA_{\text{road}}mod$. For aircraft noise (*cf.* Table 6.14), all the aircraft models led to non-significantly different results. Two models were kept for further annoyance modeling: $L_{\text{Aeq air}}rand$ and $\sigma'(N)_{\text{air}}mod$.

Total noise annoyance was then studied using combined noise experiment data. According to an ANOVA, both types of noise exposure had an influence on total annoyance, but the proportion of variance explained by urban road traffic noise is higher than the one explained by aircraft noise (*cf.* Section 2.5.1.3). Such result was already observed by Taylor [124] for *in situ* noise annoyance. He hypothesized that the influence of each source is governed by its duration of apparition. This trend of higher influence of the road traffic noise on total annoyance compared to aircraft noise is contrary to the trend observed in Chapter 2. It was hypothesized in Chapter 2 that the important contribution of aircraft noise to total annoyance may be explained by the fact that this factor included also the airport to which the respondents were exposed. Indeed, during the survey, noise exposure range is not continuous: a city is exposed to an aircraft noise of 42 dB(A), whereas the second city is exposed to an aircraft noise ranging from 52 to 54 dB(A). Aircraft noise exposure may include the non-acoustical factor of community tolerance level and other acoustical factors related to the differences between the two airports in terms of aircraft traffic and of location of the cities relative to the runways of the airports. On the other hand, in this Chapter 6, data from a combined noise experiment are considered, in which a continuous aircraft noise exposure range was considered and the aircraft flyover noises were recorded in cities exposed to the same airport, with similar location relative to the runways. Hence, this methodology may have smoothed the influence of aircraft noise exposure on total annoyance, by comparison to the survey.

From combined noise experiment data, Vos' representations showed that, in most of the combined noise situations, a strongest component phenomenon was observed (*cf.* Figure 6.2 and Appendix E). This result is confirmed by the significant correlation coefficient between mean measured total annoyance and noise annoyance calculated with the strongest component model, using mean measured partial annoyance (*cf.* Table 6.16). The other total annoyance models from literature were calculated using A-weighted equivalent noise level (L_{Aeq}) and loudness (N, *cf.* Table 6.15), measured partial annoyances (*cf.* Table 6.16) and the calculated ones (*cf.* Table 6.17). Several models were well correlated with total annoyance and were kept for further prediction of total annoyance. Standardized coefficients of these kept models were in agreement with the results of the ANOVA: urban road traffic indices contributed more to the models than aircraft indices. Retained psychophysical models were as well correlated with measured total annoyance as some perceptual models. This result was not expected as several studies have shown more differences between perceptual and psychophysical models in terms of quality of adjustment of models. Actually, perceptual models generally calculated total annoyance more adequately than psychophysical models under laboratory conditions (*e.g.* [88, 60]).

Considering survey data, a strongest component phenomenon was observed on Vos' representation (*cf.* Figures 6.3 and 6.4), as for combined noise experiment. This result was confirmed by the good correlation coefficient between total annoyance and the strongest component model, tested using individual total annoyance ratings (*cf.* Table 6.19). This common result was explained by the fact that survey noise exposure characteristics in terms of traffic and noise level range were used to construct the noise sequences evaluated during combined noise experiment. Furthermore, as the same phenomena were observed during the survey and the experiment, models developed under laboratory conditions should enable a good prediction of total annoyance measured during the survey. Considering individual total annoyance ratings (*cf.* Table 6.19), independent effect model calculated on loudness was not significantly correlated with total annoyance, whereas the other psychophysical models were significantly correlated, but with small correlation coefficients ($r \leq 0.20$). On the other hand, perceptual total annoyance models calculated on predicted individual partial annoyance (*cf.* Table 6.19) were better correlated with annoyance than psychophysical models. This shows that the computation developed to estimate the value of noise indices as a function of the L_{den}, partial and total annoyance models developed under laboratory conditions and considering noise sensitivity enabled a better *in situ* prediction of individual total noise annoyance than psychophysical models calculated on L_{den} (*cf.* Table 6.19). However, perceptual models calculated on measured partial annoyance were better correlated with individual measured total annoyance ($0.85 \leq r \leq 0.90$) than perceptual models calculated on predicted partial annoyance ($0.41 \leq r \leq 0.48$). This result showed that it is still necessary to improve the prediction of individual annoyance ratings.

4 Conclusion

In order to evaluate noise annoyance due to urban road traffic noise combined with aircraft noise, a new experiment was conducted in a simulated environment. First, the verbalizations of the participants performing this experiment were compared with the verbalization of the experiments presented in Chapters 4 and 5. This highlighted that the influential acoustical features were the same for specific and partial annoyances: global temporal variation, perceived noise intensity and timbre. Indices previously used in Chapters 4 and 5 were therefore used with noise sensitivity to propose annoyance models for urban road traffic noise and for aircraft noise, using the potential of multilevel regression to consider data stemming from different experiments.

In situ data were used to test the quality of prediction of the different models. Therefore, a methodology to estimate the values of noise indices as a function of *in situ* L_{den} was proposed. Combining this estimation with partial annoyance models enable to improve the prediction of partial annoyance ratings. Indeed, the correlation coefficient between measured partial annoyance and the predicted one was much more higher than the correlation coefficient between measured partial annoyance and L_{den}. Two models for road traffic noise and two models for aircraft noise were further used to study total annoyance.

First, total annoyance models were constructed using data of combined noise experiment. Some psychophysical and perceptual built models were selected, as they enabled a good calculation of total annoyance ratings. Second, these selected total annoyance models were tested using data of the *in situ* survey. Psychophysical models did not enable a good prediction of individual total annoyance ratings. Perceptual models using predicted partial annoyance ratings led to a better prediction than psychophysical total annoyance models, but not as good as perceptual models using measured partial annoyance ratings. Estimation of noise indices as a function of the *in situ* L_{den} and partial annoyance models improved therefore the prediction of individual total annoyance, in comparison with total annoyance models using L_{den}. This shows that improving partial annoyance prediction and the estimation of noise indices will also improve the prediction of total annoyance. Indeed, new *in situ* measurements at several positions, *i.e.* for different noise exposure situations, are necessary to assess the estimation of noise indices as a function of L_{den}; it may benefit their estimation and the quality of prediction of proposed partial and total annoyance models.

Résumé des conclusions

♣ Les caractéristiques acoustiques les plus citées pour le bruit de trafic routier urbain et pour le bruit d'avion sont : les fluctuations d'amplitude, l'intensité sonore perçue et le timbre. Ces caractéristiques mises en évidence au cours d'une expérience sur la gêne totale due à la combinaison de ces deux sources sont les mêmes que celles mises en évidence lors des expériences portant sur la gêne spécifique due à chaque source.
♣ Huit modèles pour calculer la gêne partielle due au bruit de trafic routier urbain et six modèles pour la gêne partielle due au bruit d'avion ont été proposés. Ces modèles intègrent la sensibilité au bruit des participants de l'expérience et des indices relatifs aux caractéristiques acoustiques précédemment mises en évidence.
♣ Afin de pouvoir évaluer ces modèles sur des données d'enquête *in situ*, une méthodologie est proposée pour estimer les différents indices acoustiques à partir du L_{den}.
♣ Les notes de gêne partielle mesurées lors de l'enquête sont mieux prédites par les modèles de gêne partielle précédemment proposés que par un modèle utilisant seulement l'indice L_{den}.
♣ Des modèles psychophysiques et perceptifs de gêne totale sont construits à partir des résultats de l'expérience.
♣ Lors de la confrontation aux données de l'enquête, ces modèles de gêne totale basés sur les modèles de gêne partielle et sur l'estimation des différents indices à partir du L_{den}, permettent une meilleure prédiction des jugements de gêne individuels par rapport aux modèles de gêne totale basés sur le L_{den} seul.

Et après ?

Ce chapitre a montré que les indices mis en évidence aux Chapitres 4 et 5 pour rendre compte des caractéristiques acoustiques gênantes du bruit du trafic routier urbain et du bruit d'avion sont également pertinents lors des situations de multi-exposition à ces 2 bruit. Une méthodologie a été proposée afin d'estimer *in situ* ces indices.

De nouvelles données recueillies au travers de différentes enquêtes pour des expositions plus diverses s'avèrent nécessaires pour valider à la fois les modèles de gêne partielle et totale proposés et la méthodologie d'estimation des indices. Ces résultats, en ce qui concerne à la fois la gêne en situation de mono- et de multi-exposition, militent donc pour : i) poursuivre les efforts d'amélioration de la caractérisation de la gêne en situation de mono-exposition, ii) proposer d'autres méthodologies d'estimation des indices et iii) introduire la sensibilité dans les relations exposition-réponse (*cf.* [42]).

Conclusion générale

Cette thèse avait pour objectif principal de contribuer à l'**amélioration des indicateurs de gêne pour le bruit de différentes compositions de trafic routier urbain, entendu seul et en présence de bruit d'avion**. De nombreux travaux de la littérature portant sur la gêne due aux bruits de transports ont montré l'influence de différents facteurs acoustiques (*e.g.* l'intensité perçue, le contenu spectral, le contenu temporel comme les variations irrégulières de l'amplitude [3, 28, 61, 91, 103]) mais aussi de facteurs non-acoustiques (*e.g.* la sensibilité au bruit [57, 67, 83, 117, 130, 131]). En vue de proposer des modèles de gêne pour le bruit de différentes compositions de trafic routier urbain entendu seul et en présence de bruit d'avion, les facteurs acoustiques les plus influents dans ce type d'exposition sonore doivent donc être identifiés et caractérisés par des indices pertinents.

Afin d'étudier les facteurs acoustiques influant la gêne sonore, **des expériences en conditions contrôlées ont été menées**. Quant à l'influence des facteurs non-acoustiques, elle a été étudiée à partir des **résultats d'une enquête récente menée auprès de riverains exposés aux bruits de trafic routier et d'avion** [31]. D'après Morel [87], les enquêtes *in situ* sont plus à même de permettre l'étude des facteurs non-acoustiques, puisqu'au cours des enquêtes, notamment au cours de l'enquête étudiée dans ces travaux de thèse, de nombreux facteurs non-acoustiques (*e.g.* âge, sexe, sensibilité au bruit, appréciation du cadre de vie) peuvent être mesurés, alors que le niveau sonore est souvent le seul facteur acoustique mesuré. Il a ainsi été mis en évidence par le biais de cette enquête que **l'influence de la sensibilité au bruit sur la gêne sonore était équivalente, voire supérieure à celle du L_{den}**. Ce facteur non-acoustique a donc été **mesuré lors des différentes expériences** menées en conditions contrôlées au cours de cette thèse, en vue de son intégration dans les indicateurs de gêne proposés.

Pour étudier en laboratoire la gêne due au bruit de différentes compositions de trafic routier urbain, il était nécessaire au préalable de connaître l'influence sur la gêne sonore de différents paramètres du bruit de trafic routier urbain qui interviennent lors de la construction de séquences sonores de trafic. Des expériences ont donc été menées à cet effet. Ainsi, il est apparu que **la présence de périodes de calme au sein d'une séquence diminue la gêne** due à cette séquence ; par contre, **la durée cumulée et la répartition des périodes de calme au sein des séquences sonores n'ont pas d'influence**. De même, **la gêne est influencée par la présence de certains bruits de passage particulièrement gênants** (*i.e.* les deux-roues motorisés puis les poids-lourds et bus) alors que **l'ordre des bruits de passage au sein de la séquence sonore n'influence pas la gêne** due à la séquence de trafic routier urbain.

La gêne due à des séquences sonores présentant différentes compositions de trafic routier urbain, comprenant des deux-roues motorisés, des véhicules

légers, des bus et des poids lourds, a été évaluée en laboratoire, à partir de ces résultats et en considérant des données de densité de trafic mesurées *in situ*. Les participants de l'expérience ont particulièrement remarqué **la présence de bruit de deux-roues motorisés** au sein des séquences sonores, conformément aux résultats de la littérature obtenus en laboratoire et *in situ* (*e.g.* [61, 103, 137]). Ce résultat incite à modifier le management actuel du bruit du trafic routier en considérant les deux-roues motorisés dans une catégorie distincte de celle des véhicules légers (*e.g.* [33]). De plus, les participants ont cité quatre principales caractéristiques acoustiques : **l'intensité sonore perçue, les fluctuations d'amplitude, le contenu spectral et la présence de sensations liées aux modulations**. Des indices de la littérature se sont avérés pertinents pour caractériser l'intensité sonore perçue, le contenu spectral et la présence de sensations liées aux modulations. En ce qui concerne les fluctuations d'amplitude, **un nouvel indice, $\sigma'(N)$, la valeur efficace de la dérivée temporelle de la sonie**, a été proposé. La régression multi-niveau a été utilisée pour calculer la gêne sonore, en considérant **la sensibilité au bruit associée respectivement à chacune des 3 combinaisons d'indices relatifs aux caractéristiques acoustiques citées**. La sensibilité au bruit contribue significativement aux modèles ainsi calculés.

Un protocole expérimental similaire a été mis en place afin d'étudier **la gêne due à des bruits de passage d'avion**. Les principales caractéristiques acoustiques citées par les participants sont liées **au contenu spectral, aux fluctuations irrégulières d'amplitude et à l'intensité sonore perçue**. **L'indice** $\sigma'(N)$ précédemment établi s'est avéré pertinent pour caractériser les fluctuations d'amplitude des bruits d'avion. A nouveau, la régression multi-niveau a permis de calculer la gêne sonore en considérant **la sensibilité au bruit associée respectivement à chacune des 4 combinaisons d'indices relatifs aux caractéristiques acoustiques citées**. La sensibilité au bruit contribue à nouveau fortement aux modèles ainsi construits.

Enfin, **la gêne totale en situation de multi-exposition au bruit de trafic routier urbain et au bruit d'avion** a été étudiée **en laboratoire**. Les caractéristiques acoustiques citées par les participants pour caractériser les bruits de trafic routier urbain et d'avion correspondent à celles mises en évidence lorsque les bruits étaient entendus seuls. **Les mêmes combinaisons d'indices acoustiques et psychoacoustiques** ont donc été utilisées pour proposer des modèles de gênes partielles, intégrant également **la sensibilité au bruit**. Afin d'évaluer les qualités prédictives de ces modèles en les confrontant aux données de l'enquête *in situ*, une méthodologie a été proposée afin d'**estimer les valeurs *in situ* des différents indices à partir de l'indice L_{den}**, connu pour chaque répondant de l'enquête. Ces modèles, couplés à la méthodologie d'estimation des valeurs des indices, permettent une **meilleure prédiction des notes de gêne partielle mesurée *in situ* que l'indice L_{den} seul**. À partir des données de l'expérience de multi-exposition en laboratoire, **des modèles de gêne totale ont été construits**, en utilisant soit les gênes partielles mesurées soit les gênes partielles calculées à l'aide des modèles de gêne établis en laboratoire pour chaque source de bruit. Ces modèles perceptifs, couplés à la méthodologie d'estimation des valeurs des indices, permettent **une meilleure prédiction de la gêne totale individuelle mesurée *in situ* que l'indice L_{den} seul**.

Perspectives

Cette thèse a contribué à améliorer la caractérisation physique et perceptive de la gêne due au bruit de différentes compositions de trafic routier urbain, en situation de mono-exposition et de multi-exposition avec des bruits d'avion. En effet, des modèles de gêne permettant de tenir compte à la fois de la sensibilité au bruit individuelle et des sensations influentes de la gêne due à ces bruits entendus seuls et combinés ont été proposés et testés en utilisant les données d'une enquête *in situ*.

Remplacer les cartes de bruit stratégiques actuelles, qui représentent l'exposition au bruit au moyen du L_{den}, par des cartes de gêne faciliterait la communication auprès du grand public, ce qui constitue l'un des objectifs de la directive 2002/49/CE [70]. Atteindre cet objectif nécessite d'améliorer les modèles de gêne actuels, basés uniquement sur le L_{den}. Cette thèse est donc une contribution pour atteindre cet objectif. Toutefois, des approfondissements scientifiques demeurent encore nécessaires.

Tout d'abord, les modèles proposés au cours de cette thèse pour le bruit de différentes compositions de trafic routier urbain, pour le bruit d'avion et pour les situations de multi-exposition à ces deux bruits nécessitent d'être validés sur des échantillons plus larges, en termes de population et d'exposition. En effet, la confrontation présentée ici n'a été réalisée que sur les données issues d'une enquête réalisée auprès de riverains multi-exposés.

Pour réaliser cette confrontation des modèles à des données récoltées *in situ*, la méthode d'estimation des indices à partir de la modélisation du L_{den} nécessiterait d'être approfondie. En effet, dans les temps impartis à ces travaux de thèse, cette méthode a été développée sur la base d'enregistrements de courte durée, réalisés en un seul point de prélèvement. Cette méthode nécessiterait donc d'être confrontée à des enregistrements réalisés en plusieurs points et l'évolution des valeurs des indices en fonction du niveau sonore nécessiterait d'être validée perceptivement.

De plus, seul le bruit de trafic routier urbain (vitesses inférieures à 50 km/h) a été étudié. Les modèles proposés ne sont donc pas valides pour des bruits de trafics pour lesquels la vitesse serait supérieure. La démarche de caractérisation physique et perceptive adoptée au cours de ce travail de thèse pourrait donc être utilisée afin de caractériser le bruit routier pour des vitesses supérieures à 50 km/h et pour les autres sources de bruit pour lesquelles des cartes de bruit stratégiques sont établies (*e.g.* bruit industriel, bruit ferroviaire).

Par ailleurs, les modèles de gêne proposés intègrent la sensibilité au bruit des répondants. Afin d'intégrer ces modèles dans les cartes de bruit stratégiques, la question se pose de l'estimation de ce facteur pour un très grand échantillon. En effet, ce facteur a été mesuré lors de l'enquête auprès de riverains français multi-exposés [31]. Cet échantillon ne peut donc pas être utilisé pour extrapoler la sensibilité au bruit à la population française. Une nouvelle mesure de la sensibilité sur un échantillon plus vaste et représentatif doit donc être envisagée, afin de pouvoir en estimer une loi de répartition valide pour la population française en situation d'exposition au bruit. Cela pourrait notamment permettre l'élaboration de nouvelles relations exposition-réponse, tenant compte de la sensibilité au bruit, comme proposé dans l'article [42].

Enfin, en ce qui concerne les situations de multi-exposition, les modèles perceptifs permettent une meilleure prédiction de la gêne totale individuelle que les modèles psychophysiques. Ce résultat montre qu'améliorer la caractérisation physique et perceptive des sources de bruit en situation de mono-exposition en considérant des facteurs acoustiques et non-acoustiques au sein de modèles prédictifs bénéficie également à la prédiction de la gêne en situation de multi-exposition. En utilisant les modèles perceptifs de gêne totale, des cartes de gêne totale pourraient être établies. Ces cartes permettraient notamment de tenir compte des phénomènes perceptifs mis en jeu lors des des situations de multi-exposition.

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Annexes

Annexe A

Modèle de questionnaire utilisé pour les expériences en laboratoire

1 Questionnaire

Test acoustique – ENTPE Vaulx-en-Velin Printemps 2013

Pour compléter le questionnaire ci-dessous, veuillez cochez la case correspondante à votre réponse ou formuler votre réponse si cela vous est demandé.

Concernant le test comportant des bruits de la circulation routière :

Avez-vous eu des difficultés à vous imaginer chez vous lors de l'expérience ?

☐ Oui ☐ Non

Si oui, pourquoi ? :

....
....
....
....

Sans indiscrétion, pouvez-vous me dire comment vous vous êtes imaginé chez vous ?

....
....
....
....

Avez-vous trouvé le test difficile ?

☐ Oui ☐ Non

Si oui, pourquoi ? :

....
....
....
....

Autres commentaires sur le test :

....

....
....

Concernant le test comportant des bruits d'avion :

Avez-vous eu des difficultés à vous imaginer chez vous lors de l'expérience ?

☐ Oui ☐ Non

Si oui, pourquoi ? :

....
....
....
....

Sans indiscrétion, pouvez-vous me dire comment vous vous êtes imaginé chez vous ? ....
....
....
....

Avez-vous trouvé le test difficile ?

☐ Oui ☐ Non

Si oui, pourquoi ? :

....
....
....
....

Autres commentaires sur le test :

....
....
....
....

A propos de vous et de votre environnement :

Diriez-vous que vous êtes sensible au bruit en général ?

Pour répondre à cette question, veuillez choisir un chiffre compris entre 0 et 10 correspondant au mieux à votre sensibilité au bruit en général.

0 ———————————————————— 10

Pas du tout sensible Extrêmement sensible

Quand vous êtes chez vous, êtes-vous exposé au bruit ?

Pour répondre à cette question, veuillez choisir un chiffre compris entre 0 et 10 correspondant au mieux à votre niveau d'exposition au bruit.

0 ———————————————————— 10

Pas du tout exposé Extrêmement exposé

Le cas échéant, quelle(s) est (sont) la (les) source(s) de bruit ?

....
....

....

....

Habitez-vous à proximité d'une route ? ☐ oui ☐ non

- Si oui, de quel type de route s'agit-il ? (Plusieurs réponses possibles)

☐ une nationale ☐ une autoroute ☐ un périphérique ou une voie rapide

☐ une avenue, un boulevard ☐ une petite rue

☐ Autre type de voie (*précisez*) ....

- Si oui, avez-vous une vue directe sur la route ? ☐ oui ☐ non

- Si oui, en repensant aux douze derniers mois environ, quand vous êtes chez vous, le bruit de cette route vous gêne-t-il ?

Pour répondre à cette question, veuillez choisir un chiffre compris entre 0 et 10 correspondant au mieux à votre niveau de gêne.

0 ———————————————————— 10

Pas du tout gêné — Extrêmement gêné

Habitez-vous à proximité d'un aéroport ? ☐ oui ☐ non

Si oui, lequel ? (nom et localisation)

....

- Si oui, en repensant aux douze derniers mois environ, quand vous êtes chez vous, le bruit des avions transitant par cet aéroport vous gêne-t-il ?

Pour répondre à cette question, veuillez choisir un chiffre compris entre 0 et 10 correspondant au mieux à votre niveau de gêne.

0 ———————————————————— 10

Pas du tout gêné — Extrêmement gêné

Quand vous êtes sur votre lieu de travail, êtes-vous exposé au bruit ?

Pour répondre à cette question, veuillez choisir un chiffre compris entre 0 et 10 correspondant au mieux à votre niveau d'exposition au bruit.

0 ———————————————————— 10

Pas du tout — Extrêmement

Le cas échéant, quelle(s) est (sont) la (les) source(s) de bruit ?

....

....

....

Sexe : ☐ Homme ☐ Femme

Age : ....

Profession : ....

Vous habitez ? ☐ en ville ☐ à la campagne

Votre logement actuel est : ☐ collectif (appartement) ☐ individuel (maison)

S'il s'agit d'un appartement, merci de préciser à quel étage vous habitez :

....

Merci de votre participation.

2 Ordre des sessions au sein du test d'écoute pour l'expérience II du Chapitre 3 et l'expérience du Chapitre 5

La deuxième expérience principale portant sur l'influence des facteurs du bruit de trafic routier urbain, présentée au Chapitre 3, et l'expérience portant sur les bruits d'avion, présentée au Chapitre 5, ont été réalisées au sein d'un même test. Afin de contrer un éventuel effet d'ordre dans le passage des deux sessions, la moitié des participants a d'abord réalisé la session sur les bruits d'avion puis la session sur les bruits routiers, tandis que l'autre moitié des participants les a réalisées dans l'ordre inverse.

Pour cela, nous devons tout d'abord vérifier si l'ordre de passage des sessions a eu un effet sur les notes attribuées par nos participants. Nous avons donc réalisé une ANOVA à mesures répétées sur les notes des deux sessions en prenant comme facteurs catégoriel le sens dans lequel les expériences ont été réalisées (*cf.* tableau A.1).

TABLE A.1 – Résultats de l'ANOVA à mesures répétées réalisées pour observer l'effet de l'ordre de présentation des deux sessions du test. SC : Somme totale des carrés, ddl : degrés de liberté, F : statistique de test, p : valeur de p, ϵ : valeur du facteur de correction des ddl de Huynh-Feldt, η^2 : rapport de corrélation.

Facteur	SC	ddl	F	p	ϵ	η^2
Sens	37,49	(1,31)	0,35	0,56	-	0,01
Stimuli	935,70	(28,868)	15,83	0,00	0.26	0,15
Stimuli X Sens	116,43	(28,868)	1,97	0,00	0.26	0,02

Cette ANOVA conclut à l'absence d'effet de l'ordre de présentation des deux sessions du test. Nous allons donc analyser les résultats sans tenir compte de ce facteur.

Annexe B

Modèles de régression multi-niveau

Dans cette annexe, la régression multi-niveau est explicitée plus en détail, notamment en termes d'étape intermédiaire et de représentations graphiques.

Pour rappel, une régression avec 2 niveaux est considérée : le premier niveau correspond au stimulus noté i, le deuxième niveau correspond au participant noté j. L'équation de la régression est la suivante :

$$A_{ij} = \pi_{0j} + \sum_{m=1}^{M} \pi_{mj} Index_{mi} + e_{ij} \tag{B.1}$$

$$\pi_{0j} = \beta_{00} + \beta_{01} \times Sens_j + u_{0j} \tag{B.2}$$

$$\pi_{mj} = \beta_{m0} + \beta_{m1} \times Sens_j + u_{mj} \tag{B.3}$$

$$\begin{bmatrix} u_{0j} \\ \vdots \\ u_{mj} \\ \vdots \\ u_{Mj} \end{bmatrix} \backsim \mathcal{N} \left(0, \begin{bmatrix} \sigma_{u_0}^2 & \cdots & \cdots & \cdots & \sigma_{u_{0M}} \\ \vdots & \ddots & \vdots & & \vdots \\ \sigma_{u_{m0}} & \cdots & \sigma_{u_m}^2 & \cdots & \sigma_{u_{mM}} \\ \vdots & & \vdots & \ddots & \vdots \\ \sigma_{u_{M0}} & \cdots & \cdots & \cdots & \sigma_{u_M}^2 \end{bmatrix} \right) \tag{B.4}$$

$$\text{for } m = 1, ..., M \text{ and for } j = 1, ..., J$$

$$e_{ij} \backsim \mathcal{N}(0, \sigma_e^2) \text{ for } i = 1, ..., I \text{ and } j = 1, ..., J$$

L'équation (B.1) est l'équation de la régression au niveau du stimulus. A_{ij} correspond à la note de gêne de l'individu j pour le stimulus i, π_{0j} est l'ordonnée à l'origine, π_{mj} est la pente pour la variable m ($m = 1, ..., M$) et e_{ij} est le terme d'erreur résiduel. Ce teme est supposé avoir une moyenne nulle et une variance σ_e^2, estimée lors du calcul du modèle.

Les équations (B.2) et (B.3) sont les équations de la régression au niveau du participant. La sensibilité au bruit est introduite pour expliquer les variation de l'ordonnée à l'origine et des pentes. Les termes aléatoires u_{0j} et u_{mj} sont des erreurs résiduelles au niveau du participant. Ces termes sont supposés avoir une moyenne nulle, une variance σ_{u0}^2 et σ_{um}^2, respectivement, à déterminer, et sont suppposés être indépendants des erreurs résiduelles e_{ij} au niveau du stimulus. Les coefficients de la régression β_{00}, β_{01}, β_{m0} et β_{m1} sont des paramètres fixes : ils ne varient pas selon les participants.

Les paramètres ont été introduits les uns après les autres dans l'équation. Dans la suite, le calcul sera présenté pour le cas où un seul indice acoustique est introduit dans l'équation. Pour introduire plusieurs indices, les étapes sont similaires.

1 Première étape : les modèles nuls

Tout d'abord, les modèles nuls, c'est-à-dire sans variable explicative au niveau du stimulus, sans (modèle M0a) et avec (modèle M0b) variable explicative au niveau du participant, ont été calculés. Ces modèles s'écrivent :

$$A_{ij} = \pi_{0j} + e_{ij} \tag{B.5}$$
$$\text{pour M0a} : \pi_{0j} = \beta_{00} + u_{0j} \tag{B.6}$$
$$\text{pour M0b} : \pi_{0j} = \beta_{00} + \beta_{01} \times Sens_j + u_{0j} \tag{B.7}$$
$$u_{0j} \backsim \mathcal{N}(0, \sigma^2_{u0}) \text{ for } j = 1, ..., J$$
$$e_{ij} \backsim \mathcal{N}(0, \sigma^2_e) \text{ for } i = 1, ..., I \text{ and } j = 1, ..., J$$

La gêne moyenne de chaque participant est donc égale à π_{0j}, la variation entre stimuli n'étant alors représentée que par le terme d'erreur résiduelle e_{ij}. Cette note de gêne moyenne de chaque participant est expliquée dans le modèle M0b par la variable individuelle $Sens$.

Une représentation graphique de ces modèles est proposée sur la Figure B.1.

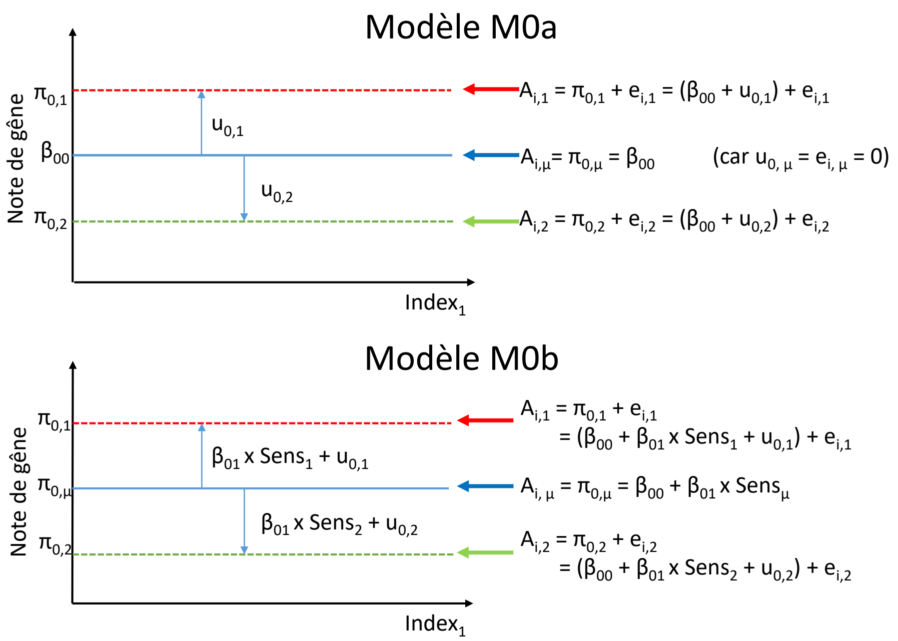

FIGURE B.1 – Représentations graphiques des modèles nuls M0a et M0b, respectivement. La courbe en pointillés rouges représente les notes de gêne du participant 1, la courbe en pointillés verts représente les notes de gêne du participant 2 et la courbe pleine bleue représente les notes de gêne moyennées sur tous les participants de l'expérience. $Sens_\mu$ représente la sensibilité moyenne calculée sur tous les participants.

2 Deuxième étape : le modèle à pente fixe

L'étape suivante consiste à introduire un indice acoustique au niveau du stimulus afin d'expliquer les variations des notes de gêne. Dans un premier temps, une pente fixe entre l'indice et les notes de gêne est considérée. Le modèle s'écrit alors :

$$A_{ij} = \pi_{0j} + \pi_{1j} Index_i + e_{ij} \tag{B.8}$$
$$\pi_{0j} = \beta_{00} + \beta_{01} \times Sens_j + u_{0j} \tag{B.9}$$
$$\pi_{1j} = \beta_{10} \tag{B.10}$$
$$u_{0j} \backsim \mathcal{N}\left(0, \sigma_{u0}^2\right) \text{ for } j = 1, ..., J$$
$$e_{ij} \backsim \mathcal{N}(0, \sigma_e^2) \text{ for } i = 1, ..., I \text{ and } j = 1, ..., J$$

Une représentation graphique du modèle à pente fixe est proposée sur la Figure B.2.

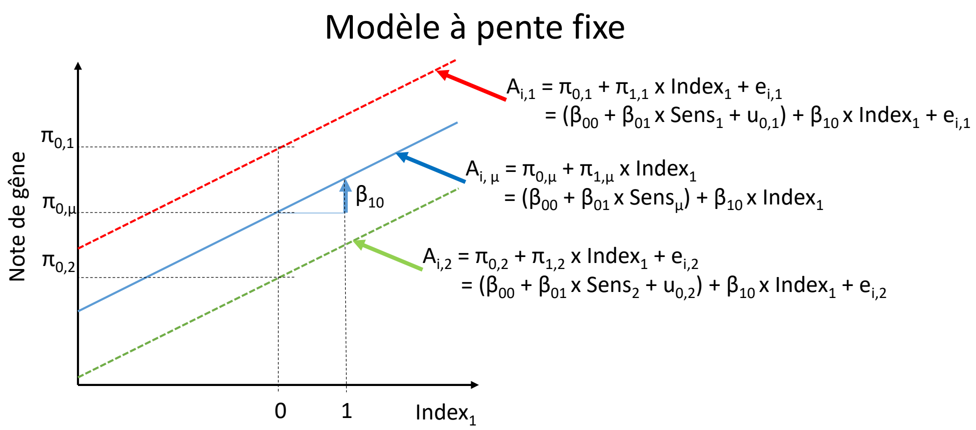

FIGURE B.2 – Représentations graphiques du modèle à pente fixe. La courbe en pointillés rouges représente les notes de gêne du participant 1, la courbe en pointillés verts représente les notes de gêne du participant 2 et la courbe pleine bleue représente les notes de gêne moyennées sur tous les participants de l'expérience. $Sens_\mu$ représente la sensibilité moyenne calculée sur tous les participants.

3 Troisième étape : le modèle à pente aléatoire

Ce modèle considère que la relation entre la gêne sonore et l'indice acoustique peut être différente pour chaque participant. Un terme aléatoire est ajouté dans l'expression de la pente individuelle. Le modèle s'écrit donc :

$$A_{ij} = \pi_{0j} + \pi_{1j} Index_i + e_{ij} \tag{B.11}$$
$$\pi_{0j} = \beta_{00} + \beta_{01} \times Sens_j + u_{0j} \tag{B.12}$$
$$\pi_{1j} = \beta_{10} + u_{1j} \tag{B.13}$$

$$\begin{bmatrix} u_{0j} \\ u_{1j} \end{bmatrix} \backsim \mathcal{N}\left(0, \begin{bmatrix} \sigma^2_{u0} & \sigma_{u01} \\ \sigma_{u01} & \sigma^2_{u1} \end{bmatrix}\right) \text{ for } j = 1, ..., J$$
$$e_{ij} \backsim \mathcal{N}(0, \sigma^2_e) \text{ for } i = 1, ..., I \text{ and } j = 1, ..., J$$

Une représentation graphique du modèle à pente aléatoire est proposée sur la Figure B.3.

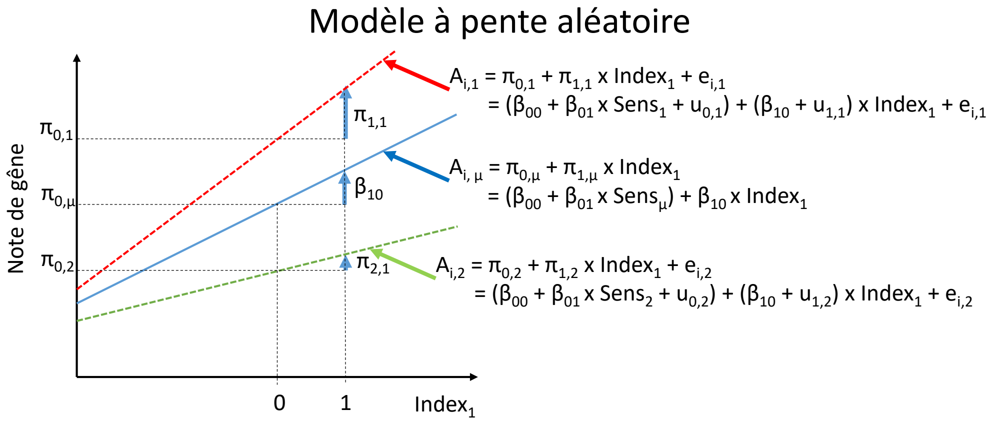

FIGURE B.3 – Représentations graphiques du modèle à pente aléatoire. La courbe en pointillés rouges représente les notes de gêne du participant 1, la courbe en pointillés verts représente les notes de gêne du participant 2 et la courbe pleine bleue représente les notes de gêne moyennées sur tous les participants de l'expérience. $Sens_{\mu}$ représente la sensibilité moyenne calculée sur tous les participants.

4 Quatrième étape : le modèle avec effet modérateur

Après avoir considéré dans le modèle à pente aléatoire que la relation entre la gêne sonore et l'indice acoustique puisse être différente pour chaque participant, le modèle à pente aléatoire considère que cette différence individuelle peut être partiellement expliquée par la sensibilité au bruit individuelle. Le terme de sensibilité au bruit est donc introduit dans l'équation de la pente comme suit :

$$A_{ij} = \pi_{0j} + \pi_{1j} Index_i + e_{ij} \tag{B.14}$$
$$\pi_{0j} = \beta_{00} + \beta_{01} \times Sens_j + u_{0j} \tag{B.15}$$
$$\pi_{1j} = \beta_{10} + \beta_{11} \times Sens_j + u_{1j} \tag{B.16}$$
$$\begin{bmatrix} u_{0j} \\ u_{1j} \end{bmatrix} \backsim \mathcal{N}\left(0, \begin{bmatrix} \sigma^2_{u0} & \sigma_{u01} \\ \sigma_{u01} & \sigma^2_{u1} \end{bmatrix}\right) \text{ for } j = 1, ..., J$$
$$e_{ij} \backsim \mathcal{N}(0, \sigma^2_e) \text{ for } i = 1, ..., I \text{ and } j = 1, ..., J$$

Une représentation graphique du modèle avec effet modérateur est proposée sur la Figure B.4.

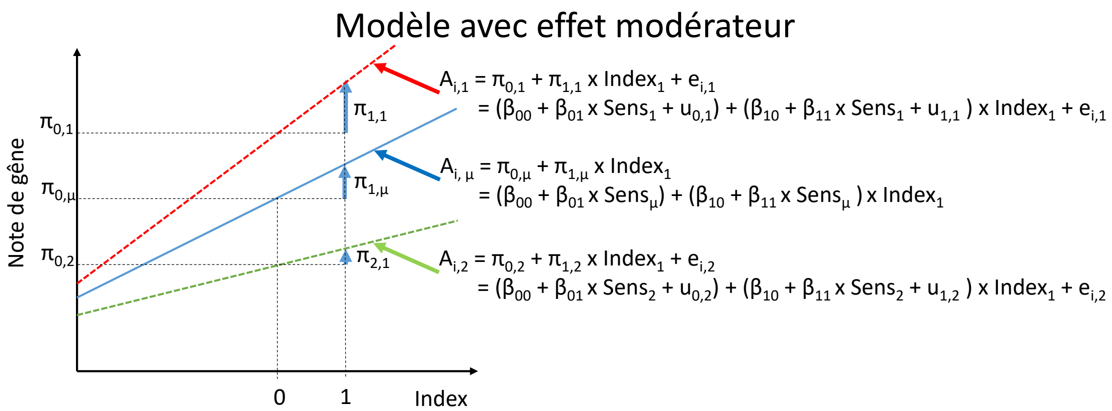

FIGURE B.4 – Représentations graphiques du modèle avec effet modérateur. La courbe en pointillés rouges représente les notes de gêne du participant 1, la courbe en pointillés verts représente les notes de gêne du participant 2 et la courbe pleine bleue représente les notes de gêne moyennées sur tous les participants de l'expérience. $Sens_\mu$ représente la sensibilité moyenne calculée sur tous les participants.

Annexe C

Noise index variation versus L_{Aeq} variation

1 Indices for the urban road traffic noise

Coefficients given in Table 6.11 were obtained by studying for several urban road traffic noise sequences the variation of the noise indices as a function of L_{Aeq}. The following Figures represent the variation of N, $\sigma'(N)$ and URA for the urban road traffic noise sequence 1T3 built and used in Chapter 4.

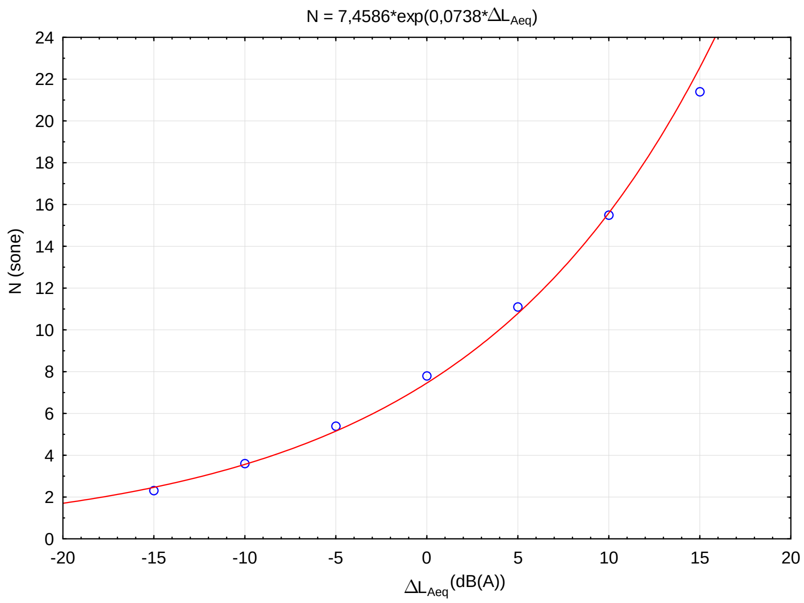

Figure C.1: Evolution of N with ΔL_{Aeq} for the urban road traffic noise sequence 1T3.

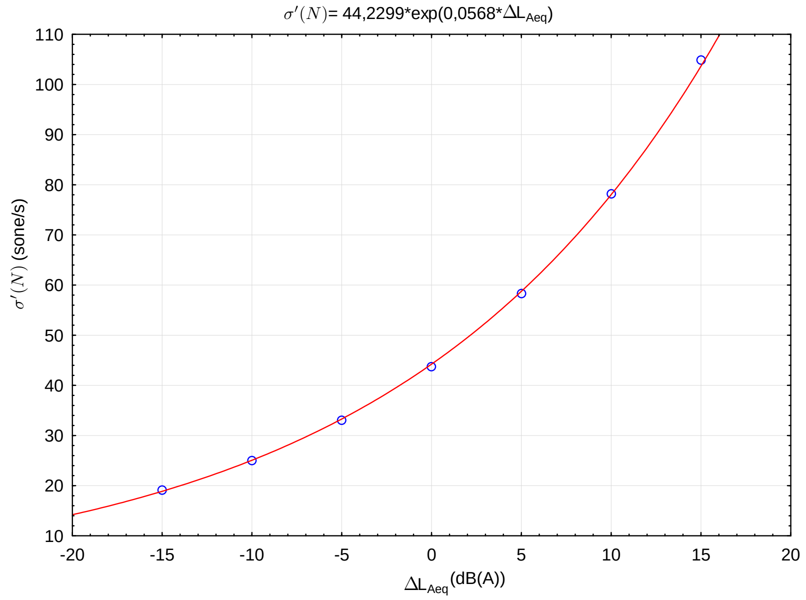

Figure C.2: Evolution of $\sigma'(N)$ with ΔL_{Aeq} for the urban road traffic noise sequence 1T3.

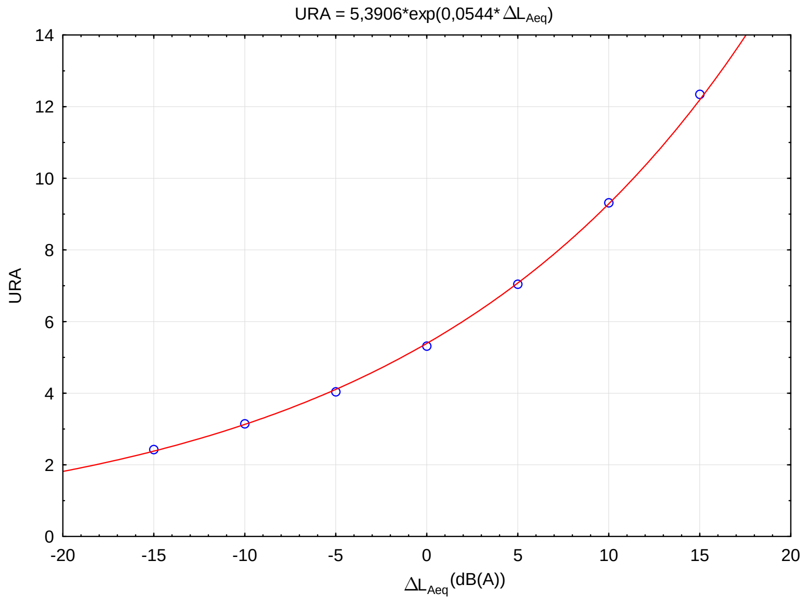

Figure C.3: Evolution of URA with ΔL_{Aeq} for the urban road traffic noise sequence 1T3.

2 Indices for aircraft noise

Coefficients given in Table 6.12 were obtained by studying for several aircraft flyover noises the variation of the noise indices as a function of L_{Aeq}. The following Figures represent the variation of N, N_{10}, $\sigma'(N)$, N_{1-12} and $TETC_{13-18}$ for the aircraft flyover noise a9 used in Chapter 5.

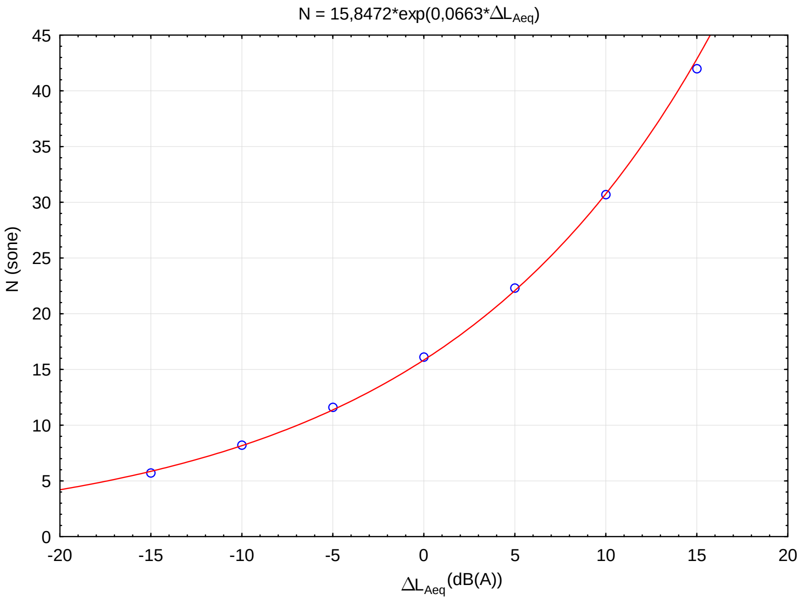

Figure C.4: Evolution of N with ΔL_{Aeq} for the aircraft flyover noise a9.

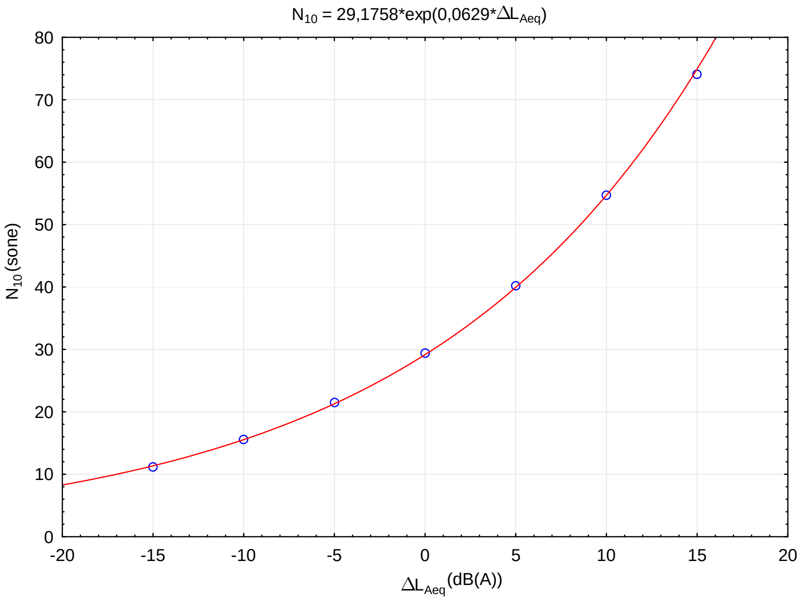

Figure C.5: Evolution of N_{10} with ΔL_{Aeq} for the aircraft flyover noise a9.

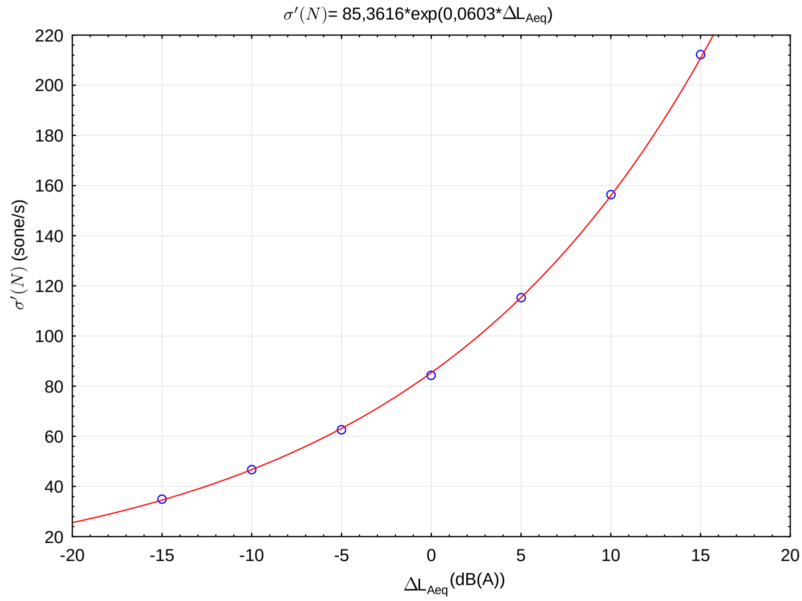

Figure C.6: Evolution of $\sigma'(N)$ with ΔL_{Aeq} for the aircraft flyover noise a9.

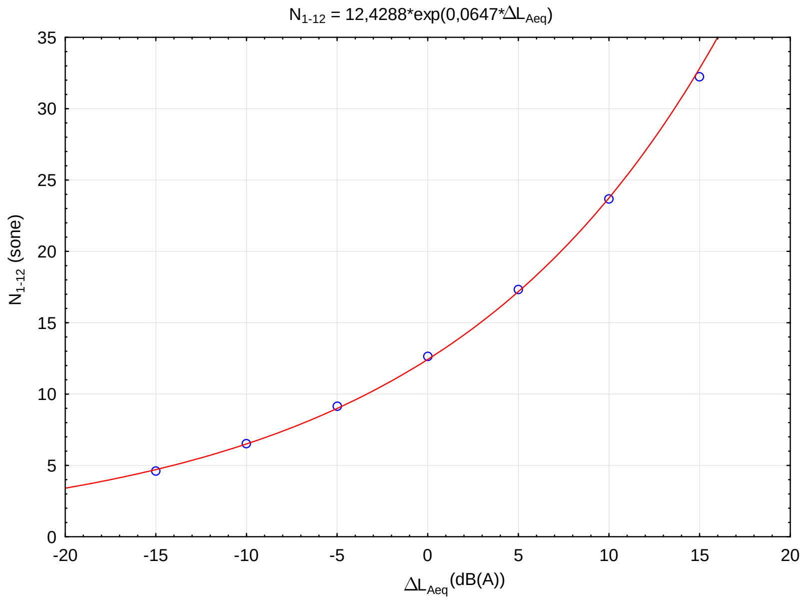

Figure C.7: Evolution of N_{1-12} with ΔL_{Aeq} for the aircraft flyover noise a9.

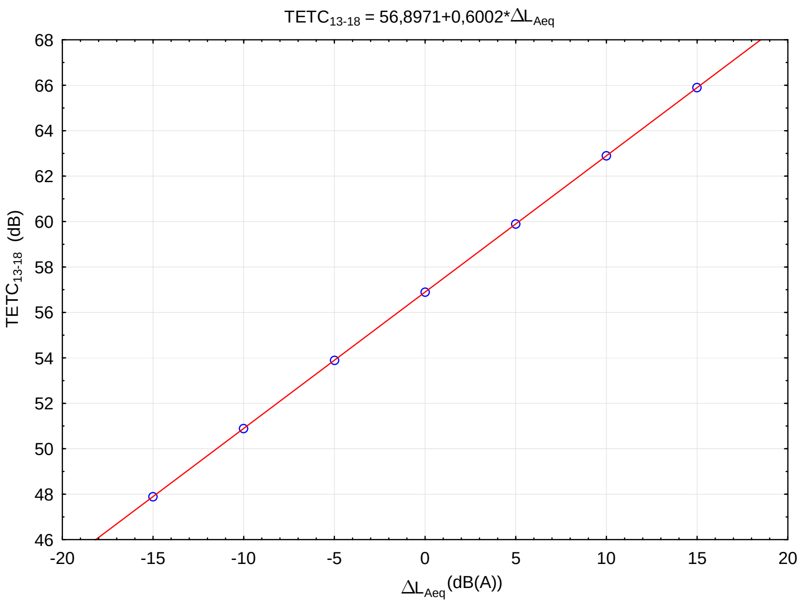

Figure C.8: Evolution of $TETC_{13-18}$ with ΔL_{Aeq} for the aircraft flyover noise a9.

Annexe D

Variation of loudness versus L_{Aeq} variation compared with the equation of Stevens [122]

In Chapter 6, a methodology is proposed to evaluate the values of several noise indices as a function of L_{den}. Therefore, the noise index variation versus equivalent noise level variation is studied, leading to the Equations 6.5 to 6.12. In particular, for loudness, the equation can be written as :

$$N = N_{mean} \times e^{(\alpha \times (L_{Aeq} - L_{Aeqmean}))} \tag{D.1}$$

with $\alpha = 0.0747$ for urban road traffic noise and $\alpha = 0.0676$ for aircraft noise.

In literature, loudness is often given as a function of sound pressure, according to the equation given by Stevens [122] :

$$N = k \times p^{0.6} \tag{D.2}$$

To know if both equations are equivalent, the following demonstration was performed :

$$N = N_{mean} \times e^{\left(\alpha \times (L_{Aeq} - L_{Aeqmean})\right)} \tag{D.3}$$

$$= \frac{N_{mean}}{e^{\left(\alpha \times L_{Aeqmean}\right)}} \times e^{(\alpha \times L_{Aeq})} \tag{D.4}$$

$$= \frac{N_{mean}}{e^{\left(\alpha \times L_{Aeqmean}\right)}} \times e^{\left(\alpha \times 20 \times \log_{10}\left(\frac{p_A}{p_0}\right)\right)} \tag{D.5}$$

with p_A the A-weighted sound pressure and p_0 the reference sound pressure, equal to 2×10^{-5} Pa.

$$N = \frac{N_{mean}}{e^{\left(\alpha \times L_{Aeqmean}\right)}} \times e^{(20\alpha \times (\log_{10}(p_A) - \log_{10}(p_0)))} \quad \text{(D.6)}$$

$$= \frac{N_{mean}}{e^{\left(\alpha \times L_{Aeqmean} + 20\alpha \times \log_{10}(p_0)\right)}} \times e^{(20\alpha \times \log_{10}(p_A))} \quad \text{(D.7)}$$

$$= \frac{N_{mean}}{e^{\left(\alpha \times L_{Aeqmean} + 20\alpha \times \log_{10}(p_0)\right)}} \times e^{\left(20\alpha \times \frac{\ln(p_A)}{\ln(10)}\right)} \quad \text{(D.8)}$$

$$= \frac{N_{mean}}{e^{\left(\alpha \times L_{Aeqmean} + 20\alpha \times \log_{10}(p_0)\right)}} \times p_A^{\frac{20\alpha}{\ln(10)}} \quad \text{(D.9)}$$

Using the previously determined α values, for urban road traffic noise, $\frac{20\alpha}{\ln(10)} = 0.649$ and for aircraft noise, $\frac{20\alpha}{\ln(10)} = 0.587$. The Equations D.1 and D.2 are therefore equivalent, if k in Equation D.2 is supposed equal to $\frac{N_{mean}}{e^{\left(\alpha \times L_{Aeqmean} + 20\alpha \times \log_{10}(p_0)\right)}}$.

The slight difference in the exponent of pressure can be explained as : i) complex sounds, with time-varying spectral content, are considered in Equation D.1 whereas Equation D.2 was determined for pure tones, and ii) as A-weighted pressure is considered in Equation D.1 whereas in Equation D.2, pressure is not weighted.

Annexe E

Vos' representations carried out on annnoyance rated in laboratory experiment presented in Chapter 6

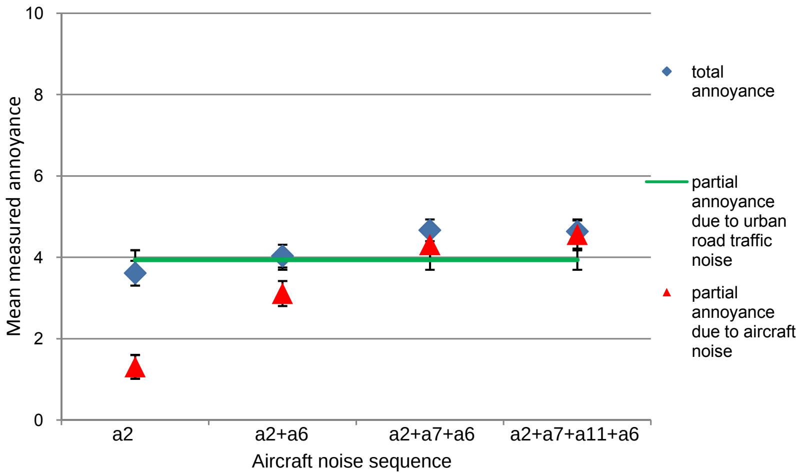

Figure E.1 – Vos' representation for the fixed urban road traffic noise (URTN) sequence 1T05 and varying aircraft noise (AN) sequence. ♦ : Mean measured total annoyance due to URTN(1T05)+AN(X), as a function of the aircraft noise sequence ; ▲ : Mean measured partial annoyance due to aircraft noise ; — : Mean measured partial annoyance due to urban road traffic noise sequence 1T05. The error bars represent the standard errors.

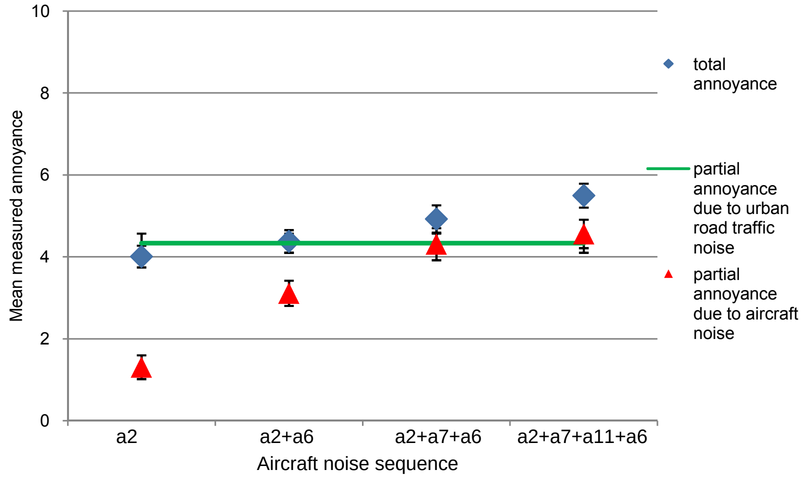

Figure E.2 – Vos' representation for the fixed urban road traffic noise (URTN) sequence 1T08 and varying aircraft noise (AN) sequence. ◆ : Mean measured total annoyance due to URTN(1T08)+AN(X), as a function of the aircraft noise sequence ; ▲ : Mean measured partial annoyance due to aircraft noise ; — : Mean measured partial annoyance due to urban road traffic noise sequence 1T08. The error bars represent the standard errors.

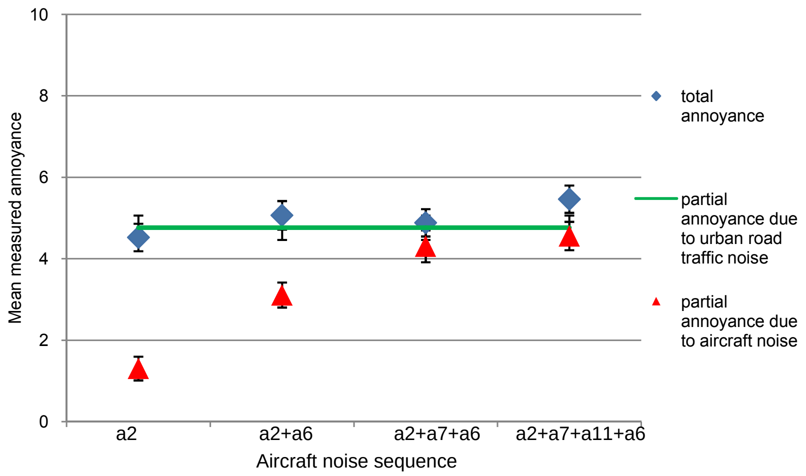

Figure E.3 – Vos' representation for the fixed urban road traffic noise (URTN) sequence 2T08 and varying aircraft noise (AN) sequence. ◆ : Mean measured total annoyance due to URTN(2T08)+AN(X), as a function of the aircraft noise sequence ; ▲ : Mean measured partial annoyance due to aircraft noise ; — : Mean measured partial annoyance due to urban road traffic noise sequence 2T08. The error bars represent the standard errors.

FOLIO ADMINISTRATIF

THESE SOUTENUE DEVANT L'ECOLE NATIONALE DES TRAVAUX PUBLICS DE L'ETAT

NOM : Gille **DATE de SOUTENANCE :** 01/07/2016

Prénoms : Laure-Anne, Louisette

TITRE : Caractérisation physique et perceptive de différentes compositions de trafic routier urbain pour la détermination d'indicateurs de gêne en situation de mono-exposition et de multi-exposition

NATURE : Doctorat **Numéro d'ordre :** 2016LYSET005

Ecole doctorale : Mécanique, Énergétique, Génie civil et Acoustique

Spécialité : Acoustique

Cote B.I.U. - / **et** **bis** **CLASSE :**

RESUME : Le bruit de la circulation routière, et en particulier le bruit des deux-roues motorisés, constituent une importante source de gêne sonore. Afin d'estimer l'exposition sonore dans les villes de plus 100 000 habitants, la directive européenne 2002/49/CE impose la réalisation de cartes de bruit stratégiques, basées sur l'indice L_{den}. Cet indice est également utilisé dans des relations exposition-réponse, afin de prédire les pourcentages de personnes gênées, notamment par le bruit du trafic routier. En couplant les cartes de bruit stratégiques et ces relations exposition-réponse, des cartes de gêne pourraient être établies. Toutefois, la pertinence de cet indice pour prédire la gêne due au bruit en milieu urbain est souvent remise en cause, car de nombreux facteurs acoustiques influents (*e.g.* les caractéristiques spectrales et temporelles) ne sont pas pris en compte par cet indice. Cette thèse vise à améliorer la caractérisation de la gêne due au bruit de trafic routier urbain en considérant différentes compositions de trafic et la présence des deux-roues motorisés. Dans ce but, des expériences sont menées en conditions contrôlées. Une première étude a porté sur l'influence de plusieurs facteurs acoustiques relatifs aux périodes de calme et aux bruits de passage de véhicules sur la gêne due au bruit de trafic routier urbain. Cette étude a conclu à l'influence de la présence de périodes de calme et du nombre de véhicules au sein du trafic routier urbain et à l'absence d'influence de l'ordre des véhicules routiers, de la position et de la durée des périodes de calme. Ces résultats ont été utilisés afin de mener la caractérisation physique et perceptive de différentes compositions de trafic routier urbain. La régression multi-niveau a été utilisée pour calculer la gêne, en considérant 1) des facteurs acoustiques influents à l'aide de combinaisons pertinentes d'indices et 2) un facteur non acoustique : la sensibilité au bruit. Dans les villes, le bruit routier est souvent entendu en situation de multi-exposition avec d'autres bruits. Dans le cadre de ces travaux de thèse, les situations de multi-exposition aux bruits routier et d'avion ont été étudiées. Pour cela, un travail semblable à celui mené pour le bruit de trafic routier urbain a été mené pour le bruit d'avion conduisant également à des combinaisons pertinentes d'indices. En vue de caractériser les gênes dues aux bruits de trafic routier et d'avion pour des situations de multi-exposition sonore, les données des précédentes expériences ainsi que celles d'une expérience conduite en situation de multi-exposition à ces bruits combinés ont été utilisées au travers d'une régression multi-niveau adaptée, comme cela a pu être mené dans la littérature. La régression multi-niveau a ainsi permis la proposition de modèles de gêne pour chaque source de bruit. Puis, la gêne totale due à des situations de multi-exposition à ces bruits a été étudiée, afin de mettre en évidence les phénomènes perceptifs mis en jeu. Des modèles de gêne totale ont été proposés, en utilisant les modèles de gêne due à chaque source. Enfin, les modèles de gêne obtenus pour chaque source et les modèles de gêne totale ont été confrontés aux données d'une enquête socio-acoustique. A cet effet, une méthodologie a été proposée afin d'estimer les différents indices des modèles à partir des valeurs du L_{den}, issues de cartes de bruit et utilisées pour définir l'exposition au bruit des personnes enquêtées. Cette confrontation a montré que les modèles proposés à partir d'expériences menées en laboratoire et couplés à la méthodologie d'estimation des indices à partir des valeurs du L_{den} permettent une bonne prédiction de la gêne *in situ*.

MOTS-CLES : gêne sonore de court-terme, gêne sonore de long-terme, bruit de trafic routier urbain, bruit d'avion, deux-roues motorisés, mono-exposition, périodes de calme, sensibilité au bruit, multi-exposition sonore, gêne totale, expérience en laboratoire, environnement simulé, enquête socio-acoustique.

Laboratoire (s) de recherche : Laboratoire Génie Civil et Bâtiment (LGCB) de l'École Nationale des Travaux Publics de l'État

Directeur de thèse: Catherine Marquis-Favre

Président de jury : Michel Bérengier

Composition du jury :

	Michel Bérengier	Président de jury
	Wolfgang Ellermeir	Rapporteur
	Catherine Lavandier	Rapporteur
	Catherine Marquis-Favre	Directrice de thèse
	Xavier Olny	Membre du jury