National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

Health effects related to wind turbine sound: an update

RIVM report 2020-0150

I. van Kamp | G.P. van den Berg

National Institute for Public Health
and the Environment
Ministry of Health, Welfare and Sport

Health effects related to wind turbine sound: an update

RIVM report 2020-0150

Colophon

DOI 10.21945/RIVM-2020-0150

I. van Kamp (task coordinator and author), RIVM
G.P. van den Berg (author), Mundonovo sound research

Contact address:	Antonie van Leeuwenhoek laan 9 3721 MA Bilthoven, Netherlands
Contracting authority:	Swiss Federal Office for the Environment (FOEN)
Contract Number:	16. 0076.PJ / S261-1003
Title Contract:	Health effects related to wind turbine sound: an update
Task coordinator:	Irene van Kamp
RIVM-project number:	E/121541/01/AA

Disclaimer: The information and views set out in this report are those of the authors and do not necessarily reflect the official opinion of FOEN. FOEN does not guarantee the accuracy of the data included in this review. Neither FOEN nor any person acting on behalf of FOEN may be held responsible for the use which might be made of the information contained therein.

Published by:
National Institute for Public Health and the Environment, RIVM
P.O. Box1 | 3720 BA Bilthoven
The Netherlands
www.rivm.nl/en

Synopsis

Health effects related to wind turbine sound: an update

Questions about health effects play a prominent role in local debates about the expansion of windfarms in the Netherlands, Switserland and elsewhere. The Swiss Federal Office for the Environment asked RIVM to review the literature published between 2017 and mid 2020 about the effects of wind turbine sound on the health of local residents.

RIVM and Mundonovo sound research collected the scientific literature on the effect of wind turbines on annoyance, sleep disturbance, cardiovascular disease and metabolism. Also, they investigated what is known about annoyance from visual aspects of wind turbines and other non–acoustic factors, such as the local decision making process.

From the literature study, annoyance clearly came forward as a consequence of sound: the louder the sound (in dB) of wind turbines, the stronger the annoyance response is. The literature did not show that so called “low frequency sound” (low pitched sound) leads to extra annoyance compared to “normal” sound. For other health effects, results of scientific research are inconsistent: these effects are not a clear consequence of the sound levels, but in some cases are related to the annoyance people experience. These results underpin previous conclusions from a comparable assignment three years ago.

The literature clearly shows that residents experience less annoyance when they participate in the siting process. By being able to take part in the siting and in balancing costs and benefits, residents experience less annoyance. It is therefore important to take worries of local residents seriously and involve them in the process of planning and the siting of wind turbines.

Keywords: wind turbine, wind farm, rhythmic sound, low-frequency sound, infrasound, health effects, annoyance, sleep disturbance

Publiekssamenvatting

Gezondheidseffecten van windturbinegeluid: een update

Vragen over gezondheidseffecten spelen een prominente rol in lokale discussies over de plannen voor uitbreiding van het windpark in Nederland, Zwitserland en elders. Het Zwitserse Federale Milieubureau vroeg het RIVM de literatuur verschenen tussen 2017 en medio 2020 op een rij te zetten, over het effect van geluid van windturbines op de gezondheid van omwonenden.

Het RIVM en Mundonovo sound research verzamelden de wetenschappelijke literatuur over het effect van windturbines op ervaren hinder, slaapverstoring, hart- en vaatziekten en de stofwisseling. Ook werd bekeken wat bekend is over hinder door de visuele aspecten van windturbines en andere niet-akoestische factoren, zoals het lokale besluitvormingsproces.

Uit de literatuurstudie blijkt dat hinder optreedt als gevolg van geluid: hoe sterker het geluid (in dB) van windturbines, hoe groter de hinder ervan. Uit de literatuur bleek niet dat het zogeheten 'laagfrequent geluid' (lage tonen) van windturbines voor extra hinder zorgt tot die gerelateerd aan "gewoon" geluid. Voor andere gezondheidseffecten zijn de resultaten van wetenschappelijk onderzoek niet eenduidig: deze effecten hangen niet duidelijk samen met het geluidniveau, maar soms wel met de ervaren hinder. Deze resultaten onderbouwen de eerdere conclusies van een vergelijkbare opdracht drie jaar geleden.

De literatuur liet duidelijk zien dat omwonenden minder hinder hebben van de windturbines als ze betrokken werden bij de plaatsing ervan. Door mee te kunnen denken over de plaatsing en de balans tussen kosten en baten, ervaren omwonenden minder hinder. Het is daarom belangrijk zorgen van omwonenden serieus te nemen en hen te betrekken bij het planningsproces en de plaatsing van windturbines.

Kernwoorden: windturbine, windpark, ritmisch geluid, laagfrequent, infrageluid, gezondheidseffecten, hinder, slaapverstoring

Contents

Summary

The siting of wind farms is a worldwide subject of public debate. Part of the opposition is based on worries about the impact on the health of residents. Immediate health effects are thought to result from visual and aural exposure. Visual exposure includes the mismatch with the landscape, shadow casting and blinking lights. Aural exposure includes the loudness and adverse characteristics of wind turbine sound: thumping or whooshing, and concerns about low frequency sound and infrasound. Apart from these potentially direct influences on human health, the process around the siting of a wind farm is an important part of the public debate. Residents often feel they have no say and must take the disadvantages without having any benefits.

RIVM and Mundonovo sound research investigated new evidence on the effects of wind turbine sound and living near a wind turbine on health to update the literature review prepared in 2017.

At equal sound levels, sound from wind turbines is experienced as more annoying than that of road or rail traffic, but wind turbine sound levels themselves are modest when compared to these other sources. Based on the new literature we conclude there is a robust association between the level of wind turbine sound and annoyance from that sound. The percentage of highly annoyed residents increases when the sound level is higher, and the visual and aural intrusion explain a large part of the annoyance of residents. Other important predictors of annoyance are noise sensitivity, attitudes towards wind turbines, health concerns and aspects related to the procedure preceding the building of a wind farm.

For other health effects of wind turbine sound, such as sleep disturbance, insomnia and cardiovascular effects the findings are inconsistent. No relation was confirmed for metabolic effects (diabetes and obesity) and mental health. Studies on cognitive effects have not been performed. We do know from studies from other noise sources that chronic annoyance can affect mental and physical wellbeing. Earlier findings on the association between symptoms and annoyance were confirmed in the new studies, but no conclusions can be drawn about the causal direction of this relation.

Although low frequency sound and infrasound might have other effects than ‘normal’ sound has, these effects are highly unlikely at sound levels typical for wind turbines. Brain studies show that low frequency and infrasound are processed in the same parts of the brain as ‘normal’ sound and there is no evidence that infrasound elicits any reaction at sub-audible levels. Acoustically low-frequency sound and infrasound differs from sound at higher frequencies: because of the low attenuation, low-frequency sound becomes relatively more important at larger distances and inside dwellings. Infrasound is attenuated even less, but coming from wind turbines it is too weak for human perception at residential locations.

These are the main conclusions of the update of the scientific literature we prepared at the request of the Swiss Federal Office for the

Environment. This report summarises the results of the literature published between 2017 and mid 2020 on the health effects of sound from wind turbines with special attention to infrasound and low-frequency sound. The search was for scientific studies and reviews concerning sound from wind turbines in combination with health effects, while admitting publications about other factors than sound. We also searched for publications about the audibility of infrasound and possible health effects specific for infrasound and low frequency sound. In the end a total of 83 publications was reviewed.

Based on the moderate effect of wind turbine sound on annoyance and the range of factors that influence the level of annoyance, we conclude that reducing the impact of wind turbine sound will profit from considering these other factors. These include attitudes towards wind turbines, health concerns, visual aspects and aspects related to the siting of wind farms. The role of factors such as participation in the planning process, procedural justice, feelings of fairness and the balance of costs and benefits from wind turbines are even more strongly supported by current evidence.

Zusammenfassung

Die Standortwahl von Windparks ist weltweit Gegenstand öffentlicher Debatten. Ein Teil der Ablehnung beruht auf der Besorgnis über die Auswirkungen auf die Gesundheit der Anwohner. Es wird angenommen, dass unmittelbare gesundheitliche Auswirkungen durch visuelle und akustische Exposition entstehen. Zur visuellen Exposition gehören die unpassende Einbindung in die Landschaft, Schattenwurf und blinkende Lichter. Die akustische Exposition umfasst die Lautstärke und die nachteiligen Eigenschaften von Windturbinengeräuschen: Pulsieren (thumping) oder Rauschen (whooshing) sowie Bedenken hinsichtlich tieffrequenter Geräusche und Infraschall. Abgesehen von diesen potentiell direkten Einflüssen auf die menschliche Gesundheit ist der Prozess rund um die Standortwahl eines Windparks ein wichtiger Teil der öffentlichen Debatte. Die Anwohner haben oft das Gefühl, dass sie kein Mitspracherecht haben und die Nachteile in Kauf nehmen müssen, ohne irgendwelche Vorteile zu genießen.

RIVM und Mundonovo sound research untersuchten neue Erkenntnisse über die Auswirkungen des Schalls von Windenergieanlagen und des Wohnens in der Nähe einer Windenergieanlage auf die Gesundheit, um die 2017 erstellte Literaturübersicht zu aktualisieren.

Bei gleichen Schallpegeln wird der Schall von Windturbinen als störender empfunden als der des Strassen- oder Schienenverkehrs, aber die Schallpegel von Windturbinen selbst sind im Vergleich zu diesen anderen Quellen bescheiden. Auf der Grundlage der neuen Literatur kommen wir zum Schluss, dass es einen robusten Zusammenhang zwischen dem Schallpegel von Windenergieanlagen und der Belästigung durch diesen Schall gibt. Der prozentuale Anteil stark belästigter Personen nimmt zu, wenn der Schallpegel höher ist, und das visuelle und akustische Eindringen erklärt einen großen Teil der Belästigung der betroffenen Bevölkerung. Andere wichtige Prädiktoren der Belästigung sind die Lärmempfindlichkeit, die Einstellung zu Windturbinen, gesundheitliche Bedenken und Aspekte im Zusammenhang mit dem Verfahren, das dem Bau eines Windparks vorausgeht.

Bei anderen gesundheitlichen Auswirkungen von Windturbinengeräuschen, wie Schlafstörungen, Schlaflosigkeit und kardiovaskulären Auswirkungen, sind die Ergebnisse inkonsistent. Für metabolische Wirkungen (Diabetes und Adipositas) und psychische Gesundheit wurde kein Zusammenhang bestätigt. Zu kognitiven Effekten wurden keine Studien durchgeführt. Wir wissen aus Studien aus anderen Lärmquellen, dass chronische Belästigung das psychische und physische Wohlbefinden beeinträchtigen kann. Frühere Erkenntnisse über den Zusammenhang zwischen Symptomen und Belästigung wurden in den neuen Studien bestätigt, aber es können keine Schlussfolgerungen über die kasuale Richtung dieses Zusammenhangs gezogen werden.

Obwohl tieffrequenter Schall und Infraschall andere Auswirkungen haben könnten als "normaler" Schall, sind diese Auswirkungen bei

Schallpegeln, die für Windenergieanlagen typisch sind, höchst unwahrscheinlich. Hirnstudien zeigen, dass tieffrequenter Schall und Infraschall in den gleichen Teilen des Gehirns verarbeitet werden wie "normaler" Schall, und es gibt keine Hinweise darauf, dass Infraschall bei Pegeln unterhalb der Hörschwelle irgendeine Reaktion hervorruft. Akustisch gesehen unterscheiden sich tieffrequenter Schall und Infraschall von Schall bei höheren Frequenzen: Aufgrund der geringen Dämpfung gewinnt tieffrequenter Schall bei größeren Entfernungen und innerhalb von Wohnungen relativ an Bedeutung. Infraschall wird noch weniger gedämpft, aber von Windenergieanlagen kommend ist er für die menschliche Wahrnehmung an Wohnstandorten zu schwach.

Dies sind die wichtigsten Schlussfolgerungen aus der Aktualisierung der Literatur, die wir im Auftrag des Schweizerischen Bundesamtes für Umwelt erstellt haben. Der vorliegende Bericht fasst die Ergebnisse der zwischen 2017 und Mitte 2020 veröffentlichten Literatur über die gesundheitlichen Auswirkungen des Schalls von Windenergieanlagen unter besonderer Berücksichtigung des Infraschalls und des tieffrequenten Schalls zusammen. Gesucht wurden wissenschaftliche Studien und Übersichtsarbeiten zum Thema Schall von Windenergieanlagen in Kombination mit gesundheitlichen Auswirkungen, wobei auch Publikationen über andere Faktoren als Schall zugelassen wurden. Wir suchten auch nach Publikationen über die Hörbarkeit von Infraschall und mögliche gesundheitliche Auswirkungen speziell für Infraschall und tieffrequenten Schall. Am Ende wurden insgesamt 83 Publikationen rezensiert.

Ausgehend von der bescheidenen Wirkung des Windturbinenschalls auf die Belästigung und der Reihe von Faktoren, die den Belästigungsgrad beeinflussen, kommen wir zum Schluss, dass eine Berücksichtigung dieser anderen Faktoren von Vorteil ist, um die Auswirkungen des Windturbinenschalls zu reduzieren. Dazu gehören die Einstellung zu Windturbinen, gesundheitliche Bedenken, visuelle Aspekte und Aspekte im Zusammenhang mit der Standortwahl von Windparks. Die Rolle von Faktoren wie Beteiligung am Planungsprozess, Verfahrensgerechtigkeit, Gefühl der Fairness und die Ausgewogenheit von Kosten und Nutzen von Windturbinen werden durch aktuelle Erkenntnisse noch stärker bekräftigt.

Résumé

L'implantation des parcs éoliens fait l'objet d'un débat public dans le monde entier. Une partie de l'opposition est basée sur les inquiétudes concernant l'impact sur la santé des populations riveraines. On estime que les effets immédiats sur la santé résultent d'une exposition visuelle et auditive. L'exposition visuelle comprend l'inadéquation avec le paysage, les ombres portées et les lumières clignotantes. L'exposition auditive comprend l'intensité sonore et les caractéristiques défavorables du son des éoliennes : battements (thumping) ou sifflements (whooshing), ainsi que les préoccupations concernant les sons de basse fréquence et les infrasons. Outre ces influences potentiellement directes sur la santé humaine, le processus entourant l'implantation d'un parc éolien est une partie importante du débat public. Les populations riveraines ont souvent l'impression de ne pas avoir leur mot à dire et de devoir subir les inconvénients sans en tirer un avantage.

Le RIVM et Mundonovo sound research ont étudié de nouvelles preuves sur les effets du bruit des éoliennes et de la vie à proximité d'une éolienne sur la santé afin de mettre à jour la revue de la littérature préparée en 2017.

À niveau sonore égal, le son provenant des éoliennes est perçu comme plus gênant que celui du trafic routier ou ferroviaire, même si les niveaux sonores des éoliennes sont modestes par rapport à ces autres sources. Sur la base de la nouvelle littérature, nous concluons qu'il existe une association robuste entre le niveau sonore des turbines éoliennes et la gêne causée par ce son. Le pourcentage de population riveraine très gênée augmente lorsque le niveau sonore est plus élevé, et l'intrusion visuelle et sonore explique une grande partie de leur gêne. D'autres indicateurs importants de la gêne sont la sensibilité au bruit, l'attitude envers les éoliennes, les préoccupations sanitaires et les aspects liés à la procédure précédant la construction d'un parc éolien. Pour d'autres effets du bruit des éoliennes sur la santé, tels que les troubles du sommeil, l'insomnie et les effets cardiovasculaires, les conclusions sont inconsistantes. Aucune relation n'a été confirmée pour les effets métaboliques (diabète et obésité) et la santé mentale. Des études sur les effets cognitifs n'ont pas été réalisées. Nous savons, grâce à des études portant sur d'autres sources de bruit, que la gêne chronique peut affecter le bien-être mental et physique. Les résultats précédents sur l'association entre les symptômes et la gêne ont été confirmés dans les nouvelles études, mais aucune conclusion ne peut être tirée sur l'orientation casual de cette relation.

Bien que les sons de basse fréquence et les infrasons puissent avoir d'autres effets que les sons "normaux", ces effets sont très peu probables aux niveaux sonores typiques des éoliennes. Des études sur le cerveau montrent que les basses fréquences et les infrasons sont traités dans les mêmes parties du cerveau que les sons "normaux" et rien ne prouve que les infrasons provoquent une réaction à des niveaux sous-audibles. Les sons et les infrasons acoustiques de basse fréquence diffèrent des sons de haute fréquence : en raison de la faible

atténuation, les sons de basse fréquence gagnent relativement en importance à grande distance et à l'intérieur des habitations. Les infrasons sont encore moins atténués, mais provenant des éoliennes, ils sont trop faibles pour être perçus par l'homme dans les lieux résidentiels.

Telles sont les principales conclusions de la mise à jour de la littérature que nous avons préparée à la demande de l'Office Fédéral Suisse de l'Environnement. Ce rapport résume les résultats de la littérature publiée entre 2017 et mi-2020 sur les effets du son provenant des éoliennes sur la santé, avec une attention particulière aux infrasons et aux sons de basse fréquence. La recherche a porté sur les études et les revues scientifiques concernant le son des éoliennes en combinaison avec les effets sur la santé, tout en admettant les publications sur d'autres facteurs que le son. Nous avons également recherché des publications sur l'audibilité des infrasons et les éventuels effets sur la santé spécifiques aux infrasons et aux sons de basse fréquence. Au final, 83 publications ont été examinées.

Sur la base de l'effet modéré du son des éoliennes sur la gêne et de l'éventail des facteurs qui influencent le niveau de gêne, nous concluons que la réduction de l'impact du son des éoliennes gagnera à prendre en compte ces autres facteurs. Il s'agit notamment des attitudes à l'égard des éoliennes, des préoccupations sanitaires, des aspects visuels et des aspects liés à l'implantation des parcs éoliens. Les preuves actuelles confirment encore plus fortement le rôle de facteurs tels que la participation au processus de planification, la justice procédurale, le sentiment d'équité et l'équilibre entre les coûts et les avantages des éoliennes.

Sommario

L'ubicazione dei parchi eolici è oggetto di dibattito pubblico in tutto il mondo. Parte dell'opposizione si basa sulle preoccupazioni per l'impatto sulla salute dei residenti. Si pensa che gli effetti immediati sulla salute derivino dall'esposizione visiva e sonora. L'esposizione visiva comprende la mancata corrispondenza con il paesaggio, la proiezione di ombre e le luci lampeggianti. L'esposizione acustica comprende il rumore e le caratteristiche avverse del suono della turbina eolica: il battimento (thumping) o il sibilo (whooshing), le preoccupazioni per il suono a bassa frequenza e gli infrasuoni. Oltre a queste influenze potenzialmente dirette sulla salute umana, il processo intorno all'ubicazione di un parco eolico è una parte importante del dibattito pubblico. I residenti spesso sentono di non avere voce in capitolo e che devono prendere gli svantaggi senza avere alcun beneficio.

RIVM e Mundonovo sound research hanno studiato nuove prove sugli effetti sulla salute del suono della turbina eolica e della vita in prossimità di una turbina eolica, per aggiornare la revisione della letteratura preparata nel 2017.

A parità di livelli sonori, il suono delle turbine eoliche è vissuto come più fastidioso di quello del traffico stradale o ferroviario, ma i livelli sonori delle turbine eoliche sono modesti rispetto a queste altre fonti. Sulla base della nuova letteratura si conclude che esiste una solida associazione tra il livello del suono delle turbine eoliche e il fastidio che ne deriva. La percentuale di residenti molto infastiditi aumenta quando il livello sonoro è più alto, e l'intrusione visiva e sonora spiega gran parte del fastidio dei residenti. Altri importanti indicatori di fastidio sono la sensibilità al rumore, l'atteggiamento nei confronti delle turbine eoliche, le preoccupazioni per la salute e gli aspetti relativi alla procedura che precede la costruzione di un parco eolico.

Per altri effetti sulla salute del suono delle turbine eoliche, come disturbi del sonno, insonnia ed effetti cardiovascolari, i risultati sono inconsistenti. Non è stata confermata alcuna relazione per gli effetti metabolici (diabete e obesità) e la salute mentale. Non sono stati effettuati studi sugli effetti cognitivi. Sappiamo da studi condotti su altre fonti di rumore che il fastidio cronico può influire sul benessere mentale e fisico. I nuovi studi hanno confermato i risultati precedenti sull'associazione tra sintomi e fastidio, ma non è possibile trarre conclusioni sulla direzione casuale di questa relazione.

Sebbene il suono a bassa frequenza e gli infrasuoni possano avere effetti diversi da quelli del suono "normale", questi effetti sono altamente improbabili ai livelli sonori tipici delle turbine eoliche. Gli studi sul cervello mostrano che le basse frequenze e gli infrasuoni sono elaborati nelle stesse parti del cervello del suono "normale" e non vi è alcuna prova che gli infrasuoni suscitino reazioni a livelli sub-udibili. Il suono a bassa frequenza acustica e gli infrasuoni differiscono dal suono a frequenze più alte: a causa della bassa attenuazione, il suono a bassa frequenza diventa relativamente più importante a grandi distanze e

all'interno delle abitazioni. L'infrasuono è attenuato ancora meno, ma proveniente dalle turbine eoliche è troppo debole per la percezione umana nelle abitazioni.

Queste sono le principali conclusioni dell'aggiornamento della letteratura che abbiamo preparato su richiesta dell'Ufficio Federale Svizzero dell'Ambiente. Questo rapporto riassume i risultati della letteratura pubblicata tra il 2017 e la metà del 2020 sugli effetti sulla salute del suono proveniente dalle turbine eoliche, con particolare attenzione agli infrasuoni e al suono a bassa frequenza. La ricerca si è concentrata su studi scientifici e recensioni riguardanti il suono proveniente dalle turbine eoliche in combinazione con gli effetti sulla salute, pur ammettendo pubblicazioni su altri fattori oltre al suono. Abbiamo anche cercato pubblicazioni sull'udibilità degli infrasuoni e sui possibili effetti sulla salute specifici per gli infrasuoni e i suoni a bassa frequenza. Alla fine sono state recensite complessivamente 83 pubblicazioni.

Basandoci sull'effetto moderato del suono della turbina eolica sul fastidio e sulla gamma di fattori che influenzano il livello di fastidio, concludiamo che la riduzione dell'impatto del suono della turbina eolica trarrà profitto dalla considerazione di questi altri fattori. Questi includono l'atteggiamento nei confronti delle turbine eoliche, le preoccupazioni per la salute, gli aspetti visivi e gli aspetti legati all'ubicazione dei parchi eolici. Il ruolo di fattori quali la partecipazione al processo di pianificazione, la giustizia procedurale, il senso di onestà e l'equilibrio dei costi e dei benefici delle turbine eoliche sono ancora più fortemente sostenuti dalle prove attuali.

1 Introduction

This report gives an update of a review we prepared in 2017 (van den Berg, van Kamp, 2017; van Kamp van den Berg, 2018) on the effects that wind turbine (WT) sound may have on the health of residents living near a wind farm. That review was based on literature up to early 2017. Since then several new studies on WT sound has been published and together they provide a better foundation for our knowledge on the effects of WT sound on residents. Similar to the 2017 review, this update emphasizes new evidence emerging from scientific publications, with peer-reviewed articles in the first place. Some scientific reports and papers presented at conferences also provide important and often reliable information and are also considered in this review.

This update is commissioned by the Noise and NIR[1] Division of the Swiss Federal Office for the Environment (Bundesamt für Umwelt). The request was to provide an updated overview of the conclusions of scientific studies with respect to the health effects of sound from wind turbines with special attention to infrasound and low frequency sound. We have collected all relevant scientific papers that were published after finishing our earlier review in January 2017.

Chapter 2 starts with some basic knowledge about the sound produced by wind turbines and the way this is heard and the sound levels that occur in practice. We use the term 'sound' to avoid the a priori implication of a negative meaning that the term noise ('unwanted sound') has. We use the term 'noise' only when that negative meaning is implied, such as in 'noise annoyance'. Chapter 2 also summarizes the general results of our earlier review.

Chapter 3 gives an overview of the evidence from recent studies about short- and long-term health effects from WT sound. Next to sound, new findings concerning the influence of personal, social and contextual and physical aspects other than sounds are reviewed. The same is done in Chapter 4, but then specifically for sound at (very) low frequencies that allegedly can affect people in other ways than 'normal' sound does. Both chapter 3 and 4 provide an overview of the new findings in conjunction with what is known, based on the earlier review in 2017. A discussion of the findings and an evaluation of the quality and results of the new studies in comparison to previous evidence can be found in Chapter 5.

Annex 1 provides a description of the search profiles used to retrieve relevant scientific information. Annex 2 gives a glossary of terms and acronyms.

[1] Non-Ionizing Radiation

2 Knowledge up to 2017

2.1 The sound of wind turbines and its perception

Referring to the review in 2017 (van den Berg and van Kamp, 2017; van Kamp and van den Berg, 2018) in this section we provide an overview of the characteristics of WT sound and the way it is produced. For modern wind turbines most of the sound produced is aerodynamical, caused by flowing air in contact with the wind turbine blades. The most important contributions are related to the atmospheric turbulence hitting the blades (inflow turbulence sound) and air flowing at the rear edge of the blade surface (trailing edge sound). Close to a wind turbine the high-pitched trailing edge sound is dominant. Due to the stronger attenuation of sound at high frequencies, at larger distance the lower pitched inflow turbulence sound becomes more dominant. Infrasound is produced by rapid changes in forces on the blades. This leads to peak levels in the infrasound range, a typical yet inaudible wind turbine 'sound signature' in measurements. The level of aerodynamic sound strongly depends on rotational speed. Therefore, sound production is highest near the fast-moving tips of the blades.

An important feature is the variation of the sound at the rhythm of the rotating blades that is described as swishing, whooshing or beating. This variation in synchrony with the blade passing frequency is also called the Amplitude Modulation (AM) of the sound.

Low frequency sound is sound below about 100 Hz to 200 Hz and is produced by road and air traffic and many other sources. Low frequency sound is included in most studies of environmental noise, as part of the normal sound range. There is less knowledge on the effects of infrasound, with a frequency below 20 Hz. Infrasound below the threshold of hearing is not a known cause of health effects, although there are indications that part of the hearing organ may react to inaudible infrasound.

Human hearing is relatively insensitive to low frequencies. This fact in combination with the sound level of the different sound components of the wind turbine cause the trailing edge sound to be the most dominant sound heard when outside and not too far from a wind turbine. Building façades attenuate higher frequencies better than lower frequencies. A consequence is that indoor sounds from an outside source have a higher proportion of low frequency sound compared to the outside sound.

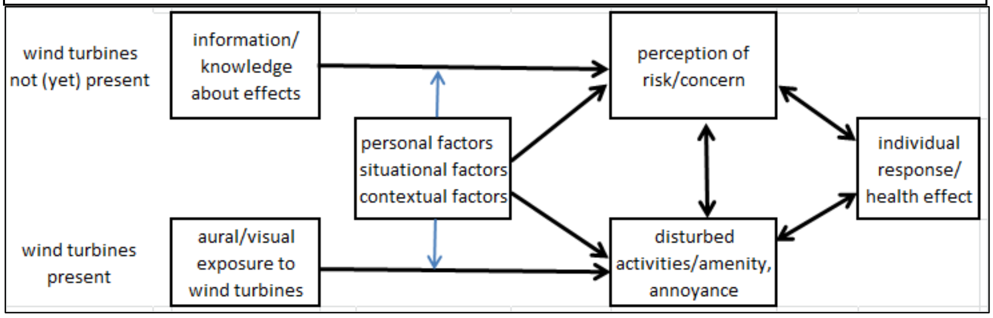
For a modern turbine, the maximum sound power level ranges between 100 to 110 dBA. For a listener on the ground at about 100 m from a turbine, the sound level will not be more than about 55 dBA. At more distant, residential locations this is less and in most studies there are few people that are exposed to an average wind turbine sound level of more than 45 dBA. The maximum steady sound level of a turbine is just a few (1 to 3) dB above the sound level averaged over a long time. When there is clearly audible whooshing or beating, the difference between the instantaneous high and low levels can go up to about 10 dB.

2.2 Effects of wind turbine sound on residents

Our 2017 review (van den Berg, van Kamp, 2017) concluded that scientific research did not provide a definite answer yet to the question whether wind turbine sound can cause health effects other than noise annoyance and if so, whether these are different from those of other environmental sound sources. It was noted that one aspect in which wind turbine sounds clearly differ from that of other sound sources is their rhythmic character, both visually and aurally.

Also, it was observed that the planning process around WT parks is often perceived as top-down with residents having no say in the plans (as is the case in many other infrastructural processes). Figure 1 illustrates how plans for wind turbine farms or actual operational wind farms can lead to disturbances and concern. This scheme shows that a number of factors can influence the effect of the (planned) turbines. The personal factors include aspects as attitudes, expectations and noise sensitivity. Situational factors include impacts such as visibility or shadow flicker, other sound sources, type of area and aesthetics. Contextual factors include aspects such as participation, the decision-making process, the siting procedure and (perceived) procedural justice.

Figure 1: A model for the relation between the exposure to (information about) wind turbines and the individual reaction



People have been shown to experience annoyance or irritation, anger or ill-being from WT sound when they feel or expect that their environmental quality will deteriorate due to the siting of wind turbines near their homes. These responses can lead to health effects in the long term. Annoyance and sleep disturbance are the most frequently studied health effects of wind turbine sound, as is the case for sound from many other sources. High degrees of noise annoyance and sleep disturbance are considered as health effects in line with the World Health Organization's (WHO) definition of health as "a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity" (WHO, 1946).

In direct relation to the WT sound, noise annoyance can be considered as the main health effect of wind turbines. At equal sound levels, sound from wind turbines is experienced as more annoying than that of road or rail traffic or industrial sources (Janssen et al, 2011). However, at residential locations wind turbine sound levels themselves are modest when compared to other sources such as road or air traffic or industrial noise. A number of studies showed that especially the rhythmic character of the sound (technically: Amplitude Modulation or AM) was experienced as annoying. We concluded that AM appeared to aggravate already existing annoyance, but AM did not lead to annoyance in people who were positive about or benefitted from wind turbines.

Evidence regarding the effect of night time wind turbine sound level on sleep was inconclusive. The available evidence did not allow to make a definite conclusion regarding sleep disturbance. However, studies did find an association between self-reported sleep disturbance and annoyance from wind turbine sound. For other health effects there was insufficient evidence for a direct relation with wind turbine sound levels. Again, studies did find an association between health effects and annoyance from wind turbine sound.
The moderate effect of the level of wind turbine sound on annoyance and the range of factors that influence the levels of annoyance imply that reducing the impact of wind turbine sound will profit from considering other factors associated with annoyance. This is equally true for other sound sources.

2.3 Effects from aspects other than sound

Next to sound, several other features came forward as being relevant for residents living in the vicinity of wind turbines. These include physical and personal aspects, and the circumstances around decision making and siting of a wind farm as well as communication and the relation between different parties involved in the process.
Visual aspects showed to play a key role in reactions to wind turbines and include the (mis-)match with the landscape, shadow casting and blinking lights. Shadow casting from wind turbines contributes to annoyance and the movement of the rotor blades themselves can be experienced as disturbing. Light flicker from the blades, vibrations and electromagnetic fields showed to play a minor role, especially in modern turbines as far as their effect on residents is concerned.

Apart from these physical factors, personal and (psycho)social factors were found to be related to annoyance. A number of studies confirmed the role of noise sensitivity in the reaction to wind turbines, independent of the sound level or sound characteristics. People who benefitted from and/or have a positive attitude towards wind turbines in their living environment generally reported less annoyance. In contrast, people who perceived wind turbines as intruding into their privacy and as detrimental to the quality of their living environment generally reported more annoyance. Attitude and media coverage show to be important elements of the complex process of siting wind turbines and affects responses. Many studies concluded that social acceptance of wind projects is highly dependent on a fair planning process and local involvement (e.g. Zaunbrecher et al 2016; Wüstenhagen et al, 2015).

3 Wind turbine sound and health

Annoyance and sleep disturbance are the most studied effects of exposure to WT sound in the living environment. More recently also cardiovascular effects (ischaemic heart disease/myocardial infarction, hypertension and stroke) as well as metabolic effects (diabetes and obesity) have been studied in people living near wind farms. Finally, there is limited evidence available on the association between WT sound and mental and cognitive effects.

Our new search of the literature over the 2017-2020 period yielded 10 reviews (including our peer reviewed paper in 2018) and 45 new articles on the association between WT sound and health of which 30 were included in the review after reading the full text.

This chapter summarizes the present state of the art regarding the knowledge available about the association between wind turbine sound and health per health outcome/effect. Each paragraph will start with a brief summary of the results from our 2017 review (van den Berg and van Kamp, 2017). Using the same search method (see annex 1 for a full description), these results were updated in this review with literature published until mid-June 2020.

New evidence on the influence of personal, situational and contextual factors on these effects is also presented in this report.

This review is primarily based on results from epidemiological studies at population level, and smaller scale laboratory experiments. Note that the description of results is limited to the effects of wind turbine sound in general in the "normal" frequency range. Findings from studies addressing specific impacts of the low frequency components and infrasound that are distinct from "normal" sound are summarized separately in Chapter 4.

3.1 Noise annoyance

In our 2017 review it was concluded that noise annoyance is the main health effect associated with the exposure to noise from an operational wind turbine. From epidemiological studies, experiments and individual narratives the typical character of wind turbine sound came forward as one of the key issues. Especially the rhythmic character of the sound (technically: Amplitude Modulation or AM) is experienced as annoying and described as a *swishing* or *whooshing* or *thumping* sound. At equal sound levels, sound from wind turbines is experienced as more annoying than that of most transport sources. Laboratory studies were inconclusive regarding the effect of amplitude modulation on annoyance. One conclusion was that there is a strong possibility that amplitude modulation is the main cause of the typical characteristics of WT sound. Another dismissed amplitude modulation as a negative factor per se, because it is highly related to attitude. A common factor is that AM appears to aggravate existing annoyance but does not lead to annoyance in persons who are positive about or benefiting from wind turbines. The general exposure-effect relation for annoyance from wind turbine sound includes all aspects that influence annoyance and thus averages over local situations. The relation can therefore form an indication only of the annoyance at local level and is not applicable to individual situations.

In our review it was noted that annoyance from wind turbines occurs at lower levels than is predominantly the case for transport or industrial sound. Based on Dutch and Swedish data an exposure-effect relation was derived between calculated sound exposure levels expressed in Lden and the percentage highly annoyed, for indoor as well as outdoor exposures. Later research confirmed these results and obtained comparable results.

3.1.1 *Reviews including annoyance*

Of the ten reviews published since 2017, four (excluding our 2017 review) address annoyance as the main health outcome. In the WHO evidence review on annoyance by Guski et al (2017) four studies on WT sound were identified. These studies were all of cross-sectional design and published before 2015. They were selected for review based on the percentage of highly annoyed (%HA) in response to a standard survey question (ISO/TS 15666:2003) referring to a particular noise source. For wind turbine noise it was concluded that evidence was only emerging, was of low quality and therefore did not allow to derive a reliable generalised Exposure Effect relation (EER). However, the WHO (2018) decided to publish a conditional EER for wind turbine noise based on 24-hour sound level average and based on this EER concluded on a preliminary threshold value of 45 dB Lden; health effects below this value were considered acceptable.

The evidence reviews for the WHO of Guski et al (2017) included studies published up to the end of 2014. In their scoping review Van Kamp et al (2020a, 2020b) provided an update of the WHO review on annoyance since then and covered the period up until the end of 2019. This identified 9 new publications (pertaining to 5 studies) on WT sound and annoyance that met the inclusion criteria.[2] Some of these studies were already included in our 2017 review. Van Kamp et al concluded that the increase of studies with large size and of moderate to good quality published since the evidence review of the WHO justifies a new meta-analysis.

The narrative review by Simos et al (2019) included 104 studies and the results are discussed along a range of determinants of annoyance. Apart from sound, these include visual aspects (shadow flicker and impact on landscape), real estate prices and safety. No meta-analysis was performed, and the inclusion criteria of studies were not clear. Annoyance was considered as a main outcome variable. Conclusion of

[2] 1.Published or accepted papers in peer-review Journals , 2.Published papers in conference proceedings, 3.Individual studies, so no reviews, meta-analyses or "commentaries", 4.In principal no language limitation, 5.Population: general population, adults; (cardiovascular effects also include children, for other outcomes not relevant or available), 6.Setting: Environmental exposure at home or at school (for children) only (NO exposure to noise in occupational setting nor in health care setting e.g. in a hospital), 7.Study design: observational studies only (NO experimental studies following the WHO protocol), for the update on cardiovascular effects and metabolic effects only case control studies and cohort studies are selected, 8.Relevant outcomes: annoyance, sleep disturbance, cardiovascular effects, metabolic effects (self-reported or clinically diagnosed)

the authors is that the evidence for an effect is meagre and that we probably deal with a 'nocebo' effect due to -in their words- 'socio-cognitive exposure', meaning that the effect of information and negative expectations lead to aversive effects (rather than the WT sound levels themselves). A set of recommendations primarily focused on the process around wind farm placements (participation, turning the farm on and off, visibility). These aspects are discussed in more detail in paragraph 3.6).

The scoping review of Freiberg et al (2019) on annoyance was performed systematically on literature published since 2000 and up to mid-2018. The review only selected articles which fulfilled the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) criteria for reporting: findings from observational studies without a selection bias, information bias, and confounder bias. It resulted in 84 articles that passed the screening and included annoyance and other health outcomes. Multiple cross-sectional studies (43) reported that wind turbine noise is associated with noise annoyance, which is moderated by several personal and contextual aspects, such as noise sensitivity, attitude towards wind turbines, or economic benefit. The authors of the review observe an increase of the number of publications since the 2010-2012 period. This is attributed to a (note: worldwide) intensified public attention –from residents, opponents, politics, and the scientific community. According to the authors, the geographical spread of the studies is not in balance with the number of wind turbine farms at location. In other words: the studies are not necessarily performed in countries where the number of wind turbines is larger: most of the research was conducted in OECD member countries. As has been concluded in other environmental fields (e.g. Baliatsas et al, 2012) the range of prevalence of noise annoyance was greater in 11 studies of lower quality, compared to the higher-quality observational studies, and might be partly due to methodological differences, sampling method, sample size and definition of the outcome. Research gaps, with respect to annoyance, concern the complex pathways of annoyance via non-acoustic factors, the objective investigation of visual wind turbine features, and the interaction between all WT related exposures.

3.1.2 Original studies on annoyance

In this section the results of the selected original studies are summarized. Some papers fall outside the time frame of 2017-2020 but are included since they were not included in our previous review and are considered relevant for the current state of knowledge. For each study we note the 'risk of bias' level as a quality assessment measure of the study and its results, determined by the PRISMA criteria described above. Sound levels in the studies are usually average sound levels at the façade of dwellings.

The Norwegian cross-sectional study by Klaeboe et al (2016) with medium risk of bias included 90 participants (response rate of 38%). Wind turbine sound levels were calculated in the range between 37 and 47 dB Lden. Annoyance was measured by the 5-point ISO standard scale. Attitudes, demographics, visual judgements and noise sensitivity were included as key confounders. Noise from wind turbines was considered more annoying than road traffic noise, equivalent to a 17–18 dB higher noise level. This is within the range of 11–26 dBA as reported by Michaud et al (2016a) and by Janssen et al (2011). It is concluded that the role of non-acoustical factors on annoyance is large, and maybe even larger than that of WT sound itself.

A new cross-sectional Polish study of Pawlaczyk et al (2018), with medium risk of bias, included 517 participants with a response rate of 78%. Wind turbine sound levels were calculated and randomly verified by in situ measurement. Noise annoyance was measured using the 5-point ISO standard scale. Residential satisfaction, visual aspects, demographics and attitude towards the WTs were included as key confounders. The percentage of participants highly annoyed (%HA) increased significantly with an increase in sound level, ranging from 35 to 53 dB Lden, and significantly increased with a negative attitude towards wind turbines as well. The %HA decreased significantly with increasing distance from the nearest wind turbine.

A Finnish study of Radun et al (2019) was graded as having low risk of bias and included 429 people (response rate 57%). Wind turbine sound level was calculated and measured and categorised in four exposure groups [25–30], [30–35], [35–40], and [40–46] dB Lden. Annoyance (indoor and outdoor) was one of the main outcomes. Trust in authorities and operators, visibility, economic benefits, age, gender, education, type of dwelling, distance were accounted for in the analysis. The sound levels [dB] were significantly associated with the percentage of participants highly annoyed (%HA) outdoor with an Odd's Ratio (OR) of 1.41. That is: an increase in exposure group corresponded to an increase in %HA outdoors by a factor of 1.41. For indoor sound level no association with annoyance was confirmed. The factor that had most influence on annoyance indoors and outdoors was health concern of the participants.

The cross-sectional study in China by Song et al (2016) with medium risk of bias, included 227 participants living close to a wind farm (response rate 77%). Wind turbine sound level was measured and categorized into 5 sound level classes (<40 dB up to >47.5 dB). Gender, age, residence time, visibility, noise sensitivity, attitude, and general opinion about WTs were included as key confounders. The %HA increased with sound level from 39.5% (95% CI: 28.4–51.4%) to 75.0% (95% CI: 50.9–91.3%).

The Health Canada's Community Noise and Health Study (CNHS) on the impact of wind turbines was extensively discussed in our 2017 review. This large cross-sectional study of high quality was performed among 1238 adult residents living at varying distances from wind turbines. One adult participant per dwelling (18–79 years), randomly selected from Ontario (n = 1011) and Prince Edward Island (n = 227), completed an in-person home interview. A strong point of the study is the high response rate of 79 percent. A-weighted as well as C-weighted outdoor sound levels were calculated and additional measurements were made at a number of locations. The results were presented in a range of publications addressing various health effects and a separate paper on the effect of shadow flicker on annoyance. Also, papers were published describing the assessment of sound levels near wind turbines and near receivers (Keith et al, 2016a), but fall outside the scope of this report. With respect to annoyance, results supported an association with exposure to wind turbine noise up to levels of 46 dBA.

Since late 2017 three additional articles were published from the CNHS: a commentary on the interpretation of findings (Michaud, et al 2018a not discussed here), a paper on the overall annoyance from WTs, taking other (non-acoustic) aspects into account (Michaud et al, 2018b) and a paper on the association between the thus derived aggregate score of annoyance and subjective health effects (Michaud et al 2018c).

The aggregate annoyance construct was developed (Michaud et al, 2018b) to account for annoyance from multiple wind turbine features: noise, blinking warning lights, vibrations, visual impact and shadow flicker. This aggregate annoyance constructs as tested in principal component analysis, explained 58–69% of the variability in total annoyance. The association with distance to the turbines was confirmed in two large samples of the CHNS sample. Annoyance significantly increased in areas between 0.550 and 1 km (mean 1.59; 95% CI 1.02, 2.15) and was highest within 550 m (mean 4.25; 95% CI 3.34, 5.16).

In the third recent paper by Michaud et al (2018c) the association of this aggregated annoyance index and a range of health complaints and symptoms was further studied. These included sleep quality, quality of life, satisfaction with health, tinnitus, migraines/headaches, and dizziness, use of medications, noise sensitivity, as well as cortisol in hair and blood pressure measures. There was a significant difference on the total annoyance scale between people who reported one or more of these symptoms (mean score 2.53 to 3.72) and people who did not (0.96 to 1.41). Conditions not related to aggregate annoyance included hair cortisol concentrations, systolic blood pressure, and rated quality of life when assessed with the single ISO standard 5-point annoyance question. It should be underscored that we are not dealing here with causal relations.

In their cross-sectional study Botelho et al (2017) compared the role of WT sound to that of annoyance in the decisions people made about noise mitigating measures. The number of participants in this study with medium risk of bias was 80, of whom 29 applied mitigating measures versus 51 who did not. Structural equation modelling (SEM) was used to estimate the effect of noise level on behaviour and of annoyance. It was concluded that decisions to insulate the home were made directly related to WT sound levels, and not to annoyance. Thus, WT sound levels are directly related to the financial consequences of taking measures to mitigate the impact on wellbeing.

A cross-sectional Finnish study by Hongisto et al (2017) with medium risk if bias was aimed at deriving an exposure-effect relation for indoor annoyance from sound from large WTs (nominal electrical power of 3 to 5 MW). The number of households with levels above 40 LAeq indoors was extremely low. This first exposure–effect relationship between outdoor sound level and indoor annoyance derived from large wind turbines was based on a sample of 429 participants around three areas with wind turbines. The relationship was consistent with those obtained for smaller wind turbines (sizes 0.15–3.0 MW) when the sound level was under 40 dB LAeq. The Community Tolerance Level (CTL), over an exposure range of 20-50 dB, was 3-4 dB lower than for two previous studies. Above 40 dB LAeq, the small number of participants prevented to make a reliable comparison to previous studies. At sound levels below 40 dB, the prevalence of high annoyance was less than 4%. The authors conclude that below 40 dB LAeq large wind turbines (>3MW) lead to similar indoor noise annoyance levels as smaller ones (<1.5 MW) do.

Schäffer et al (2019) performed a laboratory experiment with 43 participants, linking WT sound level, amplitude modulation and visual aspects to annoyance in 24 conditions combining visual and auditory stimuli. It concerned a study of high quality (risk of bias low) and of 'within subject study design': the same person tested all the conditions Annoyance was measured using the 11-point ISO scale. Both visual and acoustical characteristics were found to affect noise annoyance, besides attitude towards wind farms of the participants. An increase in sound pressure level and amplitude modulation (AM) increased annoyance, the presence of a visualised landscape decreased annoyance, and the visibility of a wind turbine increased annoyance. While simple effects of the sequence in which the stimuli were presented could be eliminated by counterbalancing, the initial visual setting strongly affected the annoyance ratings of the subsequent conditions. Due to this carryover of visual to audio effects, the annoyance due to the first visual and auditive stimuli affected what they saw and heard in later settings.

In 2018 the same group (Schäffer et al, 2018) performed a listening experiment among 52 participants, with a medium risk of bias, using stimuli representing different conditions of WT and other broadband sounds. The relative contributions of three acoustical characteristics (spectral shape, depth of periodic AM and random AM) to short-term annoyance were tested. The variation in annoyance reactions to the acoustical characteristics could be expressed as equivalent changes in WT sound pressure level. No confounders were accounted for, but perceived loudness and perceived sound characteristics were included as well as the ISO standard annoyance question adapted for acute effects. It was found that besides sound pressure level, all three characteristics affect annoyance: annoyance increased with increasing energy content in the low-frequency range as well as with depth of periodic AM and was higher in situations with random AM than without. Similar annoyance changes would be evoked by sound pressure level changes of up to 8 dB. It is concluded that sound pressure levels, spectral shape and temporal level variations affect the levels of high annoyance. The authors remark that larger scale field experiments would be needed to increase the validity of these findings in real life situations. For the impact of the visual aspects see also section 3.6.

In the cross-sectional study of Haac et al (2019), with medium risk of bias, the audibility and noise annoyance of wind turbines were evaluated. Participants (n=1043) were recruited via telephone, the web and via mail and the average response rate was 22%. In a survey respondents were asked about audibility, annoyance (not the ISO standard question), visuals aspects, level of participation in local projects and personal characteristics such as noise sensitivity, attitudes and whether they liked the "appearance" of the wind farm. WT sound levels were estimated for all the addresses and Community Tolerance Levels (CTL) -for which annoyance data as well as exposure data were also available- were calculated for participants and non-participants. This was done by linking the percentages highly annoyed persons with the WT sound levels. Results showed that WT sound level was the most robust predictor of audibility and a weak, but significant, predictor of noise annoyance. The odds for hearing a wind turbine at one's home increased by 31% [odds ratio (OR): 1.31; 95% CI (confidence interval): 1.25–1.38] for each 1 dB increase in wind turbine sound level (L1h-max), and the odds of an increase in annoyance increased by 9% (OR: 1.09; 95% CI: 1.02–1.16). Noise annoyance was best explained by visual disapproval (OR: 11.0; 95% CI: 4.8–25.4). Finally, it was shown that for people who were not receiving personal benefits from wind turbines the Community Tolerance Level (CTL) of wind turbine noise for the U.S.A. aligns with international results.

The comparative study of Hübner et al (2019) of medium risk of bias analysed a combined sample of surveys from the U.S.A, Germany and Switzerland and included 1407 (U.S.A.) and 1015 (combined data from Germany and Switzerland) respondents with a response rate of 22% over the studies. A newly developed assessment scale (Annoyance Stress or AS-Scale) was used to characterize stress-impacted individuals within populations living near turbines. This scale includes annoyance from noise and shadow flicker, and symptoms of stress. Findings indicate a low prevalence of annoyance, stress symptoms and coping strategies. The Noise Annoyance Stress or NAS-Scale (excluding shadow flicker) was negatively correlated with the perceptions of fairness of the wind project's planning and development process. Objective indicators, such as the distance to the nearest turbine and estimated sound pressure level for each respondent, were not found to be correlated to noise annoyance. Similar result patterns were found across the European and U.S. samples. In this study noise sensitivity and the attitude towards planning fairness had the strongest influences on annoyance and stress.

Pohl et al (2018) performed a longitudinal study with medium risk of bias, with 212 subjects in the first phase of which 133 participated in the second phase, while 635 were invited to participate (response rate 33%; dropout second phase 33%). Annoyance was measured making use of a standard question (5-point ISO scale), stress was measured with indicators of stress taken from earlier studies. A non-response study was performed among 104 people who did not participate. The non-responders were more often women (60.6%) than men (39.4%), and less of them had a view of a WT compared to respondents (61.5% vs. 81.6%). There were no differences in attitude towards the WT between the responders and non-responders. WT sound was recorded by the residents in this study and distance was also available as a proxy for exposure. This longitudinal study did not find empirical evidence for an association between annoyance or acceptance of WT and distance to the residence at both measurement points. More residents complained about physical and psychological symptoms due to road sound than WT sound (16%, two years later the same) than from WT sound (10%, two years later 7%). There is no numerically strong relationship between noise annoyance and the distance to the nearest WT or the estimated sound pressure level. Fairness showed to be the best predictor and annoyance was found to decrease over time. These findings are in line with previous evidence. However, WT sound (recorded by some residents) showed to be an important indicator of annoyance and stress responses. One of the key causes for WT noise annoyance might be the amplitude modulation (AM). The authors conclude that the reason why AM is so strongly linked to annoyance is the fact that short-term amplitude changes attract the attention and thus disturb current behaviour.

Krogh et al (2019) performed a qualitative study (risk of bias not relevant) among 67 study participants: 28 had vacated/abandoned their home because of the presence of a wind farm within 10 km; 31 were contemplating to do so; 4 pre-emptively vacated their home before the wind farm started operating; and 4 had decided to remain. Preliminary results showed that people with pre-existing medical conditions were concerned that living near a WT would exacerbate their symptoms. Although this study is not focussed on annoyance per se, these concerns affecting moving behaviour might also be of relevance for annoyance reactions.

3.2 Sleep disturbance

Evidence regarding the effect of night time WT sound on sleep was inconclusive in 2017. The results at the time did not allow a definite conclusion regarding both subjective and objective sleep indicators. However, studies did find a relation between self-reported sleep disturbance and annoyance from wind turbines.

3.2.1 Reviews on sleep disturbance

Based on the recently published WHO evidence review of Basner and McGuire (2018), we know that there is evidence of sufficient strength for self-reported and objective indicators of sleep disturbance due to environmental noise in general. Studies investigating the association between noise and sleep disturbance are usually based on the percentage of highly sleep disturbed (%HSD) as measured with a semi-standard question with reference to the noise source. Objective measures include motility data (movements while sleeping) and awakenings (as measured by EEG). As part of their review, Basner and McGuire conclude that the evidence for sleep disturbance from wind turbine sound is only emerging and no EER is available yet. This statement was based on self-reported sleep in six studies published in the period between 2000 and 2015 that had to meet the rigid selection criteria used. Meta-analysis was performed for five out if these six studies and led to the inconclusive results in line with several earlier reviews including our own review in 2017. A distinction was made between questions in which self-reported sleep disturbance referred to noise or sound, and studies that did not refer to WT sound in the question. This forms a potential source of bias according to Basner and McGuire. In four studies a significant association was confirmed. A meta-analysis was performed on five of the six studies based on the odds ratios for sleep disturbance for a 10 dBA increase in outdoor predicted SPL levels. Results show a non-significant association on the pooled data with an odds ratio of 1.60 (95% CI: 0.86–2.94). Two studies were identified which used an objective method (actigraphy) to evaluate sleep disturbance due to WT sound (Lane, 2016 and Michaud, 2016c). The study by Lane was too small and the large study of Michaud concluded there was no significant association between wind turbine sound levels and sleep measured with actigraphy.

In an update of studies that could expand the WHO sleep review (van Kamp et al, 2020a, 2020b) it was concluded that since 2015 a number of studies with large size and of good quality on windturbine sound was published and this justifies a meta-analysis. The search from mid-2015 to mid-2020 identified 14 new articles on sleep disturbance (11 with self-reported measures and 3 using objective measures). A new meta-analysis on subjective and objective sleep measures was suggested to assess the relation between sleep disturbance and WT sound.
The review of Micic et al published in 2018 also focused on sleep disturbance. This is a review of potential mechanisms, rather than a review of current evidence for an association between WT sound and sleep disturbance. According to the authors only a few studies have shown an association, but they consider it as plausible that WT sound leads to sleep disturbance via two mechanisms 1) chronic sleep fragmentation from frequent physiological arousals due to sensory disturbances in sleep; and 2) chronic insomnia that could develop in individuals with higher sensory acuity and/or those prone to annoyance from environmental noise.

Between 2000 and mid 2018 Freiberg et al (2019) identified 19 studies on sleep that met their criteria (described in 3.1). Most of the studies included measures of self-reported sleep disturbance and some objective sleep parameters measured with polysomnography. In higher quality studies WT sound was not associated with self-reported or objective sleep disturbance, which contrasts – at least partly – with findings from lower quality studies that more often suggest there is an association. The conclusions are broadly in line with those of Basner and Macquire (2018).

Below, the results of original studies are summarised. Some papers fall outside the time frame of 2017-2020, but are included, since they were missed in our previous review and are considered as relevant for the current state of the art.

3.2.2 *Original studies on sleep disturbance*

Lane et al (2016) performed a field experiment with a case-control design with sleep measures and diaries over a period of five nights. 27 individuals participated in the experiment of whom 15 were from a WT exposed area. The response rate was 50%. Exposures were estimated based on the distance to the nearest WT and sound levels were measured during the period of the experiment. Sleep measures included sleep onset latency (SOL), wake after onset, total sleep time, time in bed, number of awakenings and sleep efficiency. Subjective sleep was measures by the standard but adapted Pittsburgh sleep quality index. No statistically significant differences were found between the two groups on any of the objective and subjective sleep measures after adjustment for gender and age. The authors concluded that either there is no effect of WT sound on sleep, or the number of participants was too small to find such an effect, or the effect was masked by unknown factors. It was suggested that annoyance (which was not measured in this experiment) could be an important mediator between sound level and sleep quality, hereby referring to findings of Pedersen et al (2011), Persson Waye et al (2007) and Bakker et al (2012).

The Danish cross-sectional study (Poulsen et al, 2019a) made use of a cohort of 583,968 addresses and studied the association between modelled WT sound levels above 24 dB at the façade and low frequency sound level indoor and the use of prescribed sleep medication. Age, gender, income, education, marital status, type of dwelling and distance to a nearby road were included as important confounders. Results showed that a five-year averaged outdoor night time WT sound level of 42 dBA or more was weakly associated with use of sleep medication with an odds ratio (OR) of 1.14 [95% confidence interval (CI]:0.98, 1.33) per 10 dB increase. No association was found that was related to the indoor sound level. Further analysis showed the strongest associations for the older age groups. The risk of bias was estimated to be medium, since this is an ecological study, in which the data are analysed at group/population level, rather than at individual level.

In a Finish cross sectional study (Radun et al, 2019) with a low risk of bias among 429 people (response rate 57%) the association between indoor WT sound levels and self-reported sleep was studied. WT sound level was modelled and categorised (intervals: [25–30], [30–35], [35–40] and [40–46] dB Lden). Trust in authorities and operators, visibility, economic benefits, age, gender, education, type of dwelling, and distance were included as important confounders. This yielded a significant, but weak association between indoor sound level class and subjective sleep disturbance with an OR of 1.38 (1.16, 1.65) and (Nagelkerke pseudo R2=.50). However, health concerns from participants had a bigger influence on sleep disturbance than WT sound level did.

Morsing et al (2018) performed two laboratory experiments with six healthy students during three consecutive nights. Sound exposure consisted of recordings of wind turbine sound with variations in sound pressure level, amplitude modulation strength and frequency, spectral content, turbine rotational frequency and beating behaviour. Sleep was measured by polysomnographic indicators as well as questionnaires. Results showed some indications that WT sound led to objective sleep disruption, reflected by an increased frequency of awakenings, a reduced proportion of deep sleep and reduced continuous sleep stage N2. This corresponded with increased self-reported sleep disturbance. However, there was a high degree of heterogeneity between the two studies, preventing firm conclusions regarding effects of WT sound on sleep. Furthermore, there was some limited evidence from the second study that wakefulness increased with strong amplitude modulation and lower rotational frequency. The deepest sleep was adversely affected by higher rotational frequency and strong amplitude modulation, and disturbance of light sleep increased with high rotational frequency and acoustic beating. As described below, these findings were used in the development of a larger-scale sleep study (Smith et al, 2020) in a more representative study population and exposing participants to recordings of more naturalistic WT sound.

In 2020 a paper was published on a large-scale sleep experiment studying the effects of WT sound (Smith et al, 2020). For this Swedish laboratory experiment study participants were recruited from the general population aged 30-70, with a body mass index (BMI) below 30 kg/m^2, habitual sleep times between 23:00 and 07:00 and a mean sleep duration of about eight hours. Other exclusion criteria were use of sleep medication, sleep apnoea and self-reported auditory acuity which was confirmed during the first pilot night of the study. The total experiment lasted 3 nights with 1 habituation night and two nights with an exposure and control condition. WT sound was synthesized but based on many field recordings of WT sound. The AM modulation parameters used were frequency-dependent modulation depth and WT rotor speed. Random variations in time were also included to mimic the recordings. The sound was played to create an indoor sound level in a typical Swedish house resulting from a constant outdoor WT sound of 45 dBA. The time-averaged frequency spectrum was chosen to be constant in all WT sound files. Outcome measures included self-reported sleep quality and physiological measures, including polysomnography, wrist actigraphy, heart rate, blood pressure, cortisol level after awakening and long-term cortisol level from hair samples. Key confounders were subjective stress and noise sensitivity. Results showed that a single night of WT sound exposure affected the duration of the REM sleep. No effects on other measured physiologic outcomes could be detected. The findings show that continuous WT sound with AM may impact sleep according to both objective and subjective measures, leading to lower sleep quality and less restoration in the morning. This was the case for people who both were and were not habitually exposed to WT sound. When compared to the reference group in both the control and WT-night, the habitually exposed group gave a more negative rating of sleep quality and tiredness, and indicated that they slept worse than usual. They also reported higher noise-induced sleep disturbance overall in both the control and exposure night, when compared to the reference group.

The Chinese study by Song et al (2016) with 227 participants (response rate 77%) included measured WT sound levels, categorised into 5 sound levels (<40 dB up to >47.5 dB), and self-reported sleep disturbance. Gender, age, residence time, visibility, noise sensitivity, attitude and general opinion about WTs were included as important confounders. The association between LAeq from WT sound and subjective sleep was significant but weak with a Spearman correlation of .21. The risk of bias of this study was estimated as being medium.

The cross-sectional study of Kageyama et al (2016), published at the end of 2016 in Japan, among 1079 residents (response rate 47%) included field measurements during the survey on a limited set of addresses. Based on these measurements WT sound levels were estimated for each address. Sleep symptoms (self-reported) and insomnia (self-reported) were the two key outcomes. The risk of bias of this study was estimated to be medium. Sound from road traffic, noise sensitivity and attitudes towards wind turbines as well as demographic variables were accounted for. No evidence was found for an adverse effects of WT sound on physical/mental health, self-reported sleep disturbance and insomnia based on self-reported symptoms. Insomnia was found to be more prevalent in areas with WT sound levels above 40 dBA at night. Insomnia and other symptoms seemed to be primarily affected by personal features such as noise sensitivity and visual annoyance with wind turbines.

The Canadian Noise and Health (CNHS) study was discussed in our 2017 review as far as publications up to 2016 included sleep disturbance. The sleep study (Michaud et al, 2016c) among 742 participants included both subjective and objective measures and concluded that there was no effect of WT sound level on any of the sleep indicators, after adjustment for confounding such as age, caffeine use, BMI and health condition. The risk of bias was estimated to be low. No new studies on sleep were published based on the CNHS.

3.3 Cardiovascular effects

For cardiovascular effects there was insufficient evidence for a direct relation with wind turbine sound level at the time of our review in 2017.

The WHO evidence review on cardiovascular and metabolic effects prepared by van Kempen et al (2018) yielded three cross-sectional studies investigating the association between wind turbine sound and self-reported cardiovascular disease. No studies were available on the association between WT sound and diagnosed hypertension, ischaemic heart disease or stroke. An update to this review (van Kamp et al, 2020a) yielded three publications pertaining to two studies investigating the association between wind turbine noise and hypertension: one cross-sectional study (Michaud, 2018c) and one cohort study (Poulsen, 2018a). The authors of the cohort study (The Danish Wind turbine Study or DWS) concluded that their study does not support an association between wind turbine sound level and redemption of antihypertensive medication. Note that redemption of antihypertensive medication is used as an indicator of having hypertension.

We further identified and selected two new studies investigating the association between wind turbine noise and ischemic heart disease (IHD). Both were cohort studies (Poulsen 2019b; Bräuner et al, 2018). Also, the search yielded one study (Poulsen, 2019b) that investigated the association between wind turbine sound level and the incidence of stroke in a cohort study carried out in Denmark (n = 712.402). The studies by Poulsen (2019b) did not provide conclusive evidence of an association between outdoor WT sound and IHD or stroke. This finding was confirmed by the study of Bräuner et al (2018) in the so called Danish Nurse Cohort, which lend little support to a causal association between outdoor long-term WT sound exposure and IHD.

In the same Danish Nurse Cohort study, Bräuner et al (2019a) found suggestive evidence of an association between long-term exposure to WT sound and atrial fibrillation (AF) amongst female nurses. Of the 28731 nurses involved in the cohort, 1413 developed AF. They were exposed to slightly higher levels of WT sound than the controls in this study. A 30% statistically significant increased risk (95% CI: 1.05–1.61)

of AF was found amongst nurses exposed to long-term (11-year running mean) indoor WT sound levels ≥20 dBA at night compared to nurses exposed to levels <20 dBA. According to the authors, AF as a result from chronic annoyance may be a plausible explanation. However, interpretation of these findings should be cautious as exposure levels were very low.
Analysis on the same cohort (Bräuner et al, 2019b) did not yield convincing evidence for an association between long-term WT sound exposure and stroke risk.

3.4 Metabolic effects

For metabolic effects (diabetes and obesity) there was insufficient evidence for a direct relation with wind turbine sound level at the time of our review in 2017.

In the WHO evidence review on metabolic effects of environmental noise (van Kempen et al, 2018) three studies were identified and selected that investigated the association between wind turbine noise during the night and self-reported incidence of diabetes. These studies were published in Persson Waye and Pederson et al (2007), Bakker et al, (2012), and Pedersen et al (2011).
The results of the WHO review do not support an association between night time wind turbine sound level and higher risk of diabetes. The update for DEFRA published in 2020 (van Kamp et al, 2020a) yielded two new studies investigating the association between wind turbine noise and the incidence of diabetes: one cross-sectional study (Michaud, 2016b) and one cohort study (Poulsen, 2018b).

Neither in the WHO review nor in the updates nor in our literature search any studies were identified that investigated the impact of wind turbine noise on obesity.

3.5 Cognitive and mental health effects of WT sound

In the framework of the WHO Guidelines also the effects of WT sound and cognitive and mental health effects were reviewed (Clark and Paunovic, 2018). No original studies were identified on the theme of WT sound, but five systematic reviews of the evidence specifically regarding the association of wind turbine sound with quality of life, wellbeing and mental health were identified. Therefore, for wind turbine noise a review of these existing systematic reviews rather than non-existing primary research papers was undertaken. It was concluded that the number of studies was very limited and of poor quality, using a range of different outcome measures. In particular the exposure characterisation was evaluated as poor and distance was often used as a proxy for sound exposure. Based on study limitations, inconsistency and qualitative comparisons across studies the authors conclude, on very low-quality evidence, there is no substantial effect of wind turbine sound on quality of life, wellbeing or mental health. One recommendation is to also consider the spectral levels in future studies (see chapter 4).

An update of this review on cognitive and mental health effects and wellbeing, cancer, self-reported health and birth effects (Clark et al, 2020), prepared for DEFRA, showed additional evidence to conclude that

there is very low-quality evidence for an absence of effects of wind turbine sound level on self-reported quality of life or health as well as very low quality evidence of an effect on mental disorders (anxiety, depression) and birth outcomes (see also Poulsen, 2018c) . In this review no evidence was confirmed of a WT sound effect on cancer.
In the review of Freiberg et al (2019) it was concluded that no relationship was found between WT sound and stress effects and biophysiological variables of sleep; and inconsistent findings concerning sleep disturbance, quality of life, as well as mental health problems (depression and anxiety).

3.6 Social and physical aspects other than noise; influence of contextual and personal factors

Based on the evidence available about non-acoustic factors we concluded in 2017 that reducing the impact of wind turbine sound could profit from considering a large range of other factors associated with levels of annoyance due to living near a WT and the moderate effects of sound level. The influence of these factors is not necessarily unique for wind turbines, but some are.

The new search yielded some 36 new articles on the effect of situational, contextual and personal factors on annoyance and other health effects of which 25 the full text was read. Two of the articles identified were reviews on determinants of annoyance, one in general (Simos, 2019) and one on visual aspects only (Freiberg et al, 2019). Selection criteria included that the article needs to concern a study (so no commentary, editorials or opinion articles, or letters to the editor), have some reference to WT sound as well as to annoyance or other relevant outcomes. In total 24 papers were accepted for review and 12 articles were rejected because they did not meet these criteria or were already were already discussed above. In the description a distinction is made between studies addressing visual aspects, social aspects and other aspects such as personal aspects and context.

Review
The narrative review by Simos et al (2019), which was also discussed in section 3.1, included 104 articles (on 67 studies) and the results are discussed along a range of determinants. Aspects considered were WT sound, infrasound and low-frequency sounds, shadow flicker, safety, landscape impacts and real estate. At the outcome side, annoyance and the so-called wind turbine syndrome were included. Shadow flicker has been shown to have a weak association with annoyance and health indicators. Prevalence rates due to accidents around WTs are very low but only a few systematic studies on this have been performed. Results on the effect of visibility of the turbines are inconsistent. Social networks, risk perception and social acceptability have been found to be important when analysing the social aspects of wind farm development. In general, the authors conclude that there is evidence that community participation at an early phase can prevent negative perceptions associated with wind energy projects. It has been shown in several projects that housing prices drop considerably as a result of plans for WT projects. In some cases, prices returned to normal when the park

became operational. Based on the findings a set of recommendations was formulated.

3.6.1 *Visual aspects*

It has been well documented that visual aspects play an important role in the response to wind turbines. These aspects are strongly intertwined with the auditory aspect: annoyance from visual aspects may add to, or perhaps even reinforce annoyance from noise (and vice versa). Visual aspects are related not only to the visibility of the wind turbines and perceived landscape pollution, but also to other characteristics of the turbines such as blinking lights, shadow flicker and rotor blade movements.

Review

In 2019 a high-quality review was published by Freiberg et al including the literature regarding the influence of visual aspects on annoyance and sleep disturbance next to acoustical aspects. It concerns a systematic review in which the PRISMA approach was applied. The study protocol was published on the International prospective register of systematic reviews prior to the study. Seventeen studies published between 2000 and mid 2018 were included. The pooled prevalence of high annoyance due to altered views and shadow flicker was 6% each. The results of other health effects were inconsistent, with some evidence that wind turbine visibility directly increases sleep disturbance. Other studies showed that generally annoyance by visibility, shadow flicker, and blinking lights was significantly and directly associated with an increased risk for sleep disturbance. Only one study indicated an interaction effect of visual and auditory stimuli, meaning that a combination of visual and auditory aspects together leads to more sleep disturbance than sound or visual aspects separately. The authors conclude that direct and indirect wind turbine visibility may affect residents' health, and annoyance may differ between individuals.

Original studies

Several studies published since 2017 were identified on the impact of visual aspects of wind turbines in relation to their acceptability (Delicado et al, 2017; Grima-Murcia et al, 2017; Lamy et al, 2017; Frantál et al, 2017; Sklenicka and Zouhar, 2018; Landeta-Manzano et al, 2018). It concerns surveys, experiments, document analysis as well as consultation of stakeholders and experts, all aiming at mapping the role of visual aspects in the planning and decision process and exploring ways to mitigate the negative environmental and social impacts of the use of wind energy.

Delicado et al (2017) carried out media analysis, analysis of Environmental Impact Assessment reports and analysis of official positions on the issues. Visual pollution is often used in the debate and brought forward as an important argument against wind farms. Either framed negatively as a risk of damaging the image of an area or positively as indicative of a landscape presenting technological progress. Media analysis showed that the word landscape was hardly ever used, but rather the rural-urban divide came forward in opinion articles. Analysis of the EIA reports showed that objections against wind farms on grounds of landscape pollution was used more often by NGO's and in some cases by the tourism industry.

Grima-Murcia et al (2017) performed a laboratory study among 14 respondents. The respondents would see pictures of landscapes with different energy saving measures and with different durations of exposure (so a picture was shown for different lengths of time). Effects were measured by way of questionnaires and electroencephalographic recordings (EEG's). No differences were found in EEG reactions between the different stimuli including WTs. But for nuclear plants a reaction of the brain indicative of processing negative emotions was registered in the 400 msec time frame, indicating that EEG recordings can be a useful procedure for measuring visual impact.

Lamy et al (2017) held semi-structured interviews among 15 residents living at varying distances from a wind farm and visual impact came forward as one of the main aspects that influenced their perception, next to economic benefits, safety issues, noise, renewable energy benefits.

In a survey among 474 adults by Frantal et al (2017) the influence of visual aspects of the landscape itself on the impact of wind farms was studied. Results showed that the contribution was highly dependent on the local environmental and socioeconomic context. These include noise annoyance, economic benefits as well as educational level.
In a survey among 400 participants in four different central European countries (Sklenicka and Zouhar, 2018), participants were presented with a range of pictures including photoshopped wind turbines and related to three landscape planning indicators (relief, land cover and landscape pattern). The aim was to obtain an objective method, based on general principles, for predicting the visual impact of onshore wind farms. However, none of the indices showed a significant association with the acceptability of the turbines.

Landeta-Manzano et al (2018) evaluated the intervention of a leading WT manufacturer to secure acceptance of wind energy projects by local communities. This involved 47 stakeholders and 6 experts (n=53) in a qualitative study using semi-structured interviews. The focus of interventions was on the visual impact of the developments, health and safety issues, community involvement and social investment in the community. With respect to visual impact, results of the consultation showed that the most negative contributions to community acceptance are related to the location of the WT: when deciding on locations the opinion of the communities was ignored.

More technical aspects in relation to visibility, which received ample attention at an earlier stage (and were described in our 2017 review), were not identified in the new search.

In the new studies aspects of safety and electromagnetic fields due to wind turbines were also not studied or only briefly mentioned and do not add new information. We refer here to the descriptions in our 2017 review and the study of Lubner et al (2020) which is described in chapter 4.

3.6.2 *Contextual, situational and personal factors*

Research in the past decade has shed some light on the question why some people are more disturbed by wind turbines than others (Ansensio, et al 2017; Lercher et al, 2017; Haubrich, 2020). Next to physical aspects, personal and contextual aspects influence the level of annoyance. Often these aspects are referred to as non-acoustic factors, complementary to the acoustic factors expressed in decibels and Hertz. Because the term "non-acoustic" refers to a broad range of aspects, which as a result are very unspecific, we prefer the term personal and contextual factors. Thus, non-acoustic factors can be further subdivided in the following sub-categories:

- Demographic and socio-economic factors (age, gender, income, level of education);
- Personal factors (fear or worry in relation to source, noise sensitivity, economic benefit from the source);
- Situational factors (frequency of sound events, meteorological circumstances, other sound sources, distance to amenities, attractiveness of the area).
- Social and economic factors (expectation, attitudes towards producers or government, media coverage, willingness to pay and accept);

Without pretending to be exhaustive some of these aspects relevant in the framework of wind turbines are discussed in more detail below, based on the new evidence. Note that no papers were identified on situational factors.

Demographic aspects

Age, gender and educational level have not been identified as crucial predictors of noise annoyance in general. Although demographics are usually accounted for in annoyance and sleep studies and studies addressing other health outcomes, they are usually merely treated as confounders rather than as important determinants of annoyance. However, in the controversial and highly political domain of wind energy and wind turbines there is some evidence that gender and educational level do play a role.

Personal factors

Fear and noise sensitivity (NS) keep coming forward as important predictors of annoyance and stress-related effects. Noise sensitivity refers to an internal state (physiological, psychological, attitude, lifestyle and activities) of a person that increases the reactivity to sound in general. Noise sensitivity has a strong genetic component (i.e. is hereditary) but can also be a consequence of a disease (e.g. migraine) or trauma. Also, serious anxiety disorders can go together with an extreme sensitivity to sound which can in turn lead to a feeling of panic (Van Kamp and Davies, 2013). As it was in the previous period, only very few studies focus on these aspects of sensitivity and fear as the main issues related to WT sound. Several studies (Smith, 2020; Klaeboe, 2016; Michaud, 2016a; Song 2016; Kageyama, 2016), reviewed in the previous sections, included NS and sometimes fear as confounder in their statistical analysis. These studies confirm the independent role of noise sensitivity on reaction to wind turbines and this is a well-established notion also found with other noise sources. Fear and concern seem to play an increasing role in relation to low frequency noise and infrasound and the assumed link to vibroacoustic disease (see section 4.3), a disorder which is not acknowledged in the medical world as diagnosis but the notion of which contributes to fear and concern.

Social and economic aspects
Earlier studies and reviews have emphasized that for the social acceptance of wind turbine projects by a local community it is crucial how the community evaluates the consequences for their future quality of life. Next to physical aspects, situational, social and political aspects play an important role on acceptance as well as on feelings of fairness. The communication and relation between the key parties (residents, (local) authorities, project developer) is crucial in this regard. In the past 10 years we can observe an increasing polarisation between these key parties.

Since our previous review in 2017, we first noticed an increasing number of studies investigating the social acceptance of wind projects by local communities in a number of countries. Many of these studies stress the relevance of a fair planning process and local involvement and participation (Beuret, 2016) (Brennan, 2017) (Langer, 2017) (Liebe, 2017) (MacDonald, 2017) (Scherhaufer, 2017) (Sonnberger, 2017) (Kongprasit , 2018) (Clark and Botterill, 2018) Janhunen, 2018) (Kim, 2018) (Gölz, 2018)(Langer, 2018), (Landeta-Manzano, 2018) (Scherhaufer, 2018) (Sæþórsdóttir 2018). Remarkably the number of articles lately seems to decline: no new articles were identified after 2018. In the studies on social acceptance of wind projects by local communities, it is concluded overall that people are more willing to accept new turbines in their vicinity if they can participate in decision making, or the turbines are owned by a group of citizens, and/or if the generated electricity is consumed in the region instead of being exported. Also, people who are already exposed to WT sound near their homes are more willing to accept the wind farm than newly exposed groups. Several researchers emphasise that local circumstances may differ considerably and should be accounted for in a study on acceptance. They emphasise that a complex set of individual and collective values and preferences should be considered, and the perspectives of scientists, policymakers and citizens should hereby be integrated.

An interesting paper by Clark et al (2018) argues that different stakeholders with different interests contribute different "facts" about the legitimacy of health complaints. The wind turbine syndrome is an example of an illness that is controversial in the medical world and therefore leads to ample debate. This finding shows how the interests and legitimacy of arguments are particularly relevant for competing descriptions of the 'facts' of wind turbine health effects.
Earlier studies concluded that economic aspects can also affect annoyance from wind turbines. Co-ownership and benefit came forward

as important predictors in counterbalancing adverse responses to WT. It was emphasised that not only benefits are important in this context, but also a sense of control (van den Berg et al, 2008). This was confirmed in the CNHS and to a lesser degree to studies in Japan.

More recent literature into the social and economic aspects is focussed more on *willingness to pay* and *willingness to accept* and the perceived reduction in housing values related to wind farms (Wen et al, 2018; Thomson, 2018). Thomson concluded that residents near a WT would, on average, be willing to pay for a windfarm to stay, whereas people living near a coal plant were willing to pay for the coal plant to be removed. Demographics did not have a significant effect on these results. In contrast to these findings and based on a systematic review Wen et al (2018) concluded that respondents in different studies consistently showed increasing *willingness to pay* for moving wind farms to greater distances from their dwellings. But this also strongly depended on the number and height of WT and this might indicate that we are not dealing with a linear association.

4 Health effects specific for low frequency sound and infrasound

As stated in our earlier review, a range of residential health effects are attributed to the presence of wind turbines and infrasound and/or low-frequency sound is sometimes mentioned as an important cause of these effects, also when the infrasound levels must be very low or are unknown. It was noted in section 2.1 that acoustically low-frequency sound and infrasound is different from sound at higher frequencies. When compared to sound at higher frequencies low-frequency sound and infrasound is attenuated less over larger distances and through building façades. However, here we want to know about the effects: can infrasound or low-frequency sound have effects on people that are different from effects of normal sound? In this chapter the question is addressed whether infrasound or low-frequency sound deserves special consideration with respect to the effects of wind turbine sound.
Most of the new studies involved measuring brain activity in response to infrasound, often in comparison to low-frequency or ‘normal’ sound. So, in contrast to chapter 3 the focus here is more on mechanisms that play a role and less so on long term health effects of low-frequency and infrasound. We will use the term audio sound for sounds at intermediate and higher frequencies, that is: at frequencies above about 100 Hz to 200 Hz. Thus audio sound is similar to what we mean by ‘normal sound’ except for an overlap where low-frequency sound merges with audio sound –with no clear boundary between the two sound ranges. Below we will describe the results from these studies.

4.1 Audibility of infrasound and low-frequency sound

In our 2017 review (Van den Berg and Van Kamp, 2017) we noted that low-frequency sound can be heard daily from road and air traffic and many other sources. Low-frequency sound is usually included as part of the normal frequency range of everyday sounds. Less is known about infrasound and the perception of infrasound is not as common as it is for low-frequency or ‘normal’ sound. However, infrasound is not unique for wind turbines; it is produced by natural sources (storm, surf), big animals, and transport and man-made machinery at levels comparable to what wind farms produce. Due to the high threshold of hearing, we are usually not aware of most of this infrasound.

The new literature search yielded 24 publications, of which 17 papers were relevant for this update, two of them dating before 2017. They include two reviews, thirteen original experimental studies, one cross-sectional field study and one desk study. Two newly published experimental studies (Maijala et al, 2020 and Krahé et al, 2020) were included after closing the search, thus resulting in 19 relevant papers.

There are several new studies on the possible effects of sounds of low frequency on persons: how do people respond when exposed to a low-pitched sound or even to an inaudible infrasound? Immediate or short-term reactions can be investigated in an experimental study with short sound samples in a laboratory setting. Longer lasting or long-term

reactions are usually investigated in field studies where many people in their own environment are exposed to a number of environmental sources including the one under study, such as a wind farm. Several of the studies reviewed here are part of the European EARS II project on infrasound and ultrasound. This was a follow-up to the first EARS project that expired in 2015. With respect to infrasound the conclusion of this first project was that below about 20 Hz the perception seems to change, and possibly other sensory processes give input to the auditory cortex. Also, for sound levels slightly below the hearing threshold regions of the brain were active that process emotional activity (EARS Communiqué, 2015).
An important part of the EARS II project was to investigate brain activity in persons exposed to infrasound, including inaudible infrasound. The EARS II project closed in 2019. Koch (2017) presented an overview of results of the project, including studies mentioned below.

Behler and Uhlenkamp (2020) report on the loudness and unpleasantness of sound of either 8 Hz or 32 Hz when presented over 1.5 seconds at the right ear of 19 young, normal hearing persons. The maximum sound level used was 140 dB (presumably to prevent any hearing damage). They furthermore measured brain activity when the same persons were exposed to the sounds in an MRI-scanner. The individual hearing thresholds at 32 Hz varied from about 60 to 80 dB, at 8 Hz from 90 to 115 dB; these threshold values are comparable to thresholds known from literature. On average the unpleasantness of each sound changed linearly with the perceived loudness, but individually there were large variations. In the MRI-scanner the sounds were again presented at the right ear, now at either low or medium loudness according to each person's individual loudness scaling. At low loudness (5 out of the maximum 50 loudness units) for both tones there was some activity in the auditory cortex at both sides of the brain. At medium loudness (35 out of 50 loudness units) there was significant activity at the same brain locations. The auditory cortex is the location in the brain were sound is known to be processed and this study shows that this is also true for infrasound. Activation of the auditory cortex in this study was found to correlate better with perceived loudness than with the actual sound level.

In another laboratory study Burke et al (2019) investigated whether the ability to hear a sound was influenced by the presence of another sound. For example: if an infrasound tone without any other sound is just audible, will it still be audible when audio-sound is added? This was tested with 13 young, normal hearing participants using two infrasound tones (5 Hz and 12 Hz) two audio-sound tones (100 Hz and 1000 Hz), and pink noise between 250 and 4000 Hz. First, for each individual the threshold was measured three times and generally for each participant the three outcomes varied over a 5-dB range. Between participants the hearing thresholds varied over 20 dB or more. All thresholds were in the range of thresholds known from literature. Second, a soft audio-sound (5 dB over the threshold of that sound) was added to either the 5 or 12 Hz infrasound. This did not significantly influence the detection threshold for the infrasound. However, the presence of a louder audio-sound (50 dB over the threshold of that sound) on average did lead to a raise of the detection threshold of the infrasound. This shift was significant and ranged from 1 to 9 dB, depending on frequency. In a third experiment it was tested if adding infrasound would change the detection threshold for audio-sound. The detection threshold of audio-sound was tested in the presence of 5 or 12 Hz infrasound. The infrasound levels were very low: either sub-audible (10 dB below the hearing threshold) or barely audible (5 or 10 dB above the hearing threshold) There was no significant effect of the infrasound on the detection threshold of the audio-sound. Thus, a medium loud audio-sound raises the detection threshold for infrasound. But a (very) soft audio-sound has no effect on the audibility of infrasound and vice versa.

Burke et al (2019) remark that sound is known to mask other sound of comparable or higher frequency, making the other sound less or not audible. It was therefore unexpected that the audio-sounds could partially mask sound of a much lower frequency. They conclude that apparently masking of infrasound is different from masking audio sounds. However, they also remark that the presence of audio-sound may draw attention to that sound, away from the soft infrasound. In that case, the shift in detection threshold would be les a consequence of audibility and more an effect of attention. The authors of this study also note that there is a correlation between the individual detection thresholds of the two infrasound tones and between the individual detection thresholds of the audio-sounds, but there is no correlation between the infrasound and audio-sound thresholds. They suggest that this could be a result from different detection mechanisms for infrasound and audio-sound.

Weichenberger et al (2017) investigated the effect of infrasound and low-frequency sound at discrete frequencies on brain activity. The hearing thresholds were determined for the right ear of 14 young, normal hearing participants at eight frequencies ranging from 8 to 125 Hz. All thresholds were in the range of thresholds known from literature. After that the participants estimated the loudness at each frequency for sound levels up to the maximum of 124 dB. From these estimates for every participant a medium loud level was determined for the 12 Hz infrasound.
In the MRI-scanner participants were exposed to three different conditions: the medium-loud 12 Hz tone was presented to the right ear at either the medium-loud level or 2 dB below the individual threshold, or no sound was presented. Each condition lasted 200 seconds, which is relatively long. When exposed to the medium loud infrasound no corresponding brain activity showed up. The authors speculate that this may be due to adaptation of the neurons: with a constant stimulus the activation decreases over time. As a result, averaged over the 200 seconds of exposure, the brain activation was not strong enough to show up in the measurements. This contrasts with results of an earlier study with almost the same test persons and the same instrumentation (Weichenberger et al, 2015). In that study the participants were exposed to short bursts (3 seconds) of 12 Hz and medium loudness infrasound, which resulted in significant brain activity in the auditory cortex.
Exposure to the 12 Hz infrasound at a level just beneath their individual hearing threshold elicited brain activity not found in the other two conditions. This activity occurred in the auditory cortex and two other

brain areas associated with conflict regulation and emotional processing. According to the authors the brain activity at sub-audible level shows there is an unconscious reaction of the body and they speculate that for prolonged exposure there might be a 'potential link' with 'the emergence of various physiological as well as psychological health effects'.

Krahé et al (2020) did an extensive experimental study with 39 participants of whom 16 were 'predisposed': they had requested authorities or an engineering firm to investigate a problem with infrasound at their home. All participants were exposed to four different infrasounds and complete silence, each for half an hour, in a very quiet, home-like room in a remote building. The infrasound was presented at three frequencies (3 Hz modulated, 5 and 10 Hz unmodulated) at levels close to a standard threshold used in Germany and at 10 dB above this threshold at a frequency of 18 Hz. It was expected that some participants would be able to hear the sound and some not. The results show that, on average, the participants perceived the silence period as not annoying, the period with lower frequencies (3 and 5 Hz) as somewhat annoying, with higher frequencies as moderately annoying. However, for most sounds (3, 10, 18 Hz) individual scores covered the entire scale from not annoying to very annoying. For the 5 Hz and the silent period scores ranged from not to rather annoying. Participants perceived the 18 Hz sound as rumbling and humming, the others sounds as rumbling and pulsating. Predisposed participants were not found to react differently from the other participants. The authors conclude that 'essentially' perception is sensed by the ears, even when there is not always a hearing sensation.

Jurado and Marquardt (2020a) investigated the use of EEG as a means to measure the perceived loudness of a very low-frequency sound. With a technique called Frequency Following Response (FFR), electrodes on the head picked up neural activity that was measured as a function of the loudness of the sound. With this, they measured the brain response to a constant sound of either 11 or 38 Hz in 11 young, normal hearing participants. The general trend was that at zero loudness (sound at hearing threshold) the measured signal was close to the background of electric noise in the brain. Generally, with increasing loudness the signal at first increased relatively steeply and above a low to medium loudness remained constant. However, there were large individual differences from this trend and the authors concluded that the FFR signal that was measured here did not correlate with the loudness perceived by the participants. They conclude that FFR is not a useful method to measure loudness.

In another study Marquardt and Jurado (2018) investigated the perception of amplitude modulation in wind turbine sound: if we hear swishing or beating in wind turbine sound, is that just the sound level variation in the WT audio-sound with the frequency of blades passing the tower, or is there an (added) effect of the infrasound peak at that same frequency? The perception of the (simplified) phenomenon was investigated for two sounds at discrete frequencies and either a modulation of the tone at 8 Hz or an 8 Hz infrasound tone added to the unmodulated sound. The variation in the amplitude (strength) of the modulated 63 or 125 Hz sound was 25% or 37.5% of the original tone amplitude. With a separate test the level of the 8 Hz infrasound was determined that would give the same loudness to the combination of infrasound plus 63/125 Hz compared to the amplitude-modulated 63/125 Hz tone. Then, all the different sounds of each 1.2 second duration were played many times in random order, with a total of 400 samples. 12 normal hearing, young participants had to decide for every sample if it contained infrasound. For each of the different sounds the percentage of correct answers was not significantly different from what one can expect from pure guessing. The authors conclude that a combination of a tone together with a constant 8 Hz infrasound is similar to our ears to the tone amplitude modulated at 8 Hz (without the infrasound): we cannot hear a difference between both.

Jurado and Gordillo (2019) investigated if fluctuations in the level of a low-frequency sound influenced the perceived loudness of that sound. This was tested with 24 young, normal hearing participants who matched the loudness of three simple low-frequency tones (40, 63 or 80 Hz) and one 1000 Hz tone with a number of tone combinations. Each combination consisted of two tones close in frequency to one of the three simple tones. The combination produces fluctuations (variations in amplitude) at a frequency equal to the difference in the frequencies of both tones. The differences in frequency were 1, 2, 5 and 12 Hz. The results show that the effect of fluctuation at the lower frequencies on loudness was modest and corresponded to 2 dB or less. The results were in agreement with what was already known in literature and loudness models.

Based on a number of publications, including some mentioned above, in their review Carlile et al (2018) summarize that small differences in the infrasound hearing threshold can result in large differences in sensation because of the steep increase of loudness at infrasound frequencies. This was already reported by Moller and Pedersen (2004) and the more recent studies (Koch et al, 2017) have confirmed this.

4.2 Effect of lower frequencies compared to ‘normal’ sound

Infrasound and low-frequency sound from wind turbines have been suggested to affect the health of residents in a way other than audio-sound does, but at the time of our 2017 review there was little scientific evidence to support this hypothesis. Other effects, such as vibration of the body, nausea or dizziness, have been shown to occur in laboratory experiments, but only at higher levels of infrasound compared to those from wind turbines. Here we will also review studies that may reveal specific effects of infrasound and low-frequency sound, regardless whether they include wind turbines or not.

In his narrative review of the possible effects of infrasound from wind turbines Tonin (2017) concludes that a large number of measurements have shown that wind turbine infrasound is below the threshold of hearing. There is disagreement about whether this means it cannot have an effect. He notes a lack of studies in which persons are ‘intentionally subjected to infrasound and a response is measured’. However, in recent years some relevant laboratory studies have been published and these will be summarized below.

In a large survey in the Netherlands Van Kamp et al (2017) asked residents in three cities if they were annoyed by a low-frequency 'humming' noise, for example from ventilators. 7% of the almost 4000 participants in this study were highly annoyed by such noise. Other noise sources (road traffic, construction works, mopeds and neighbours) each led to higher numbers of annoyed persons, ranging from 13% to 22% of the participants. Some sources (rail traffic and industry) led to less annoyance (each about 4%). Persons dissatisfied with their residential situation as well as noise-sensitive persons reported more annoyance compared to people scoring high on residential satisfaction and/or low on noise sensitivity. In the daytime the percentage of persons highly annoyed by humming sounds was higher when background sound levels from road traffic were higher. At night the reverse was true: a higher background level was related to somewhat less annoyance from humming sounds. There was no correlation between annoyance from humming sounds and sound insulation at the façade (double glazing, wall cavity wall filling, absorbing ventilation grille).

As, according to a conference paper by Krahe (2019) "low-frequency noise is strongly annoying", he devised a method to rate the annoyance from WT low-frequency and infrasound. This was done by giving a penalty when the sound had one or more annoying features such as pulsating or a rhythmic variation in level or a tonal quality. From this, penalties were calculated based on knowledge of the annoyance of each feature. The calculated penalty values were compared to the assessments of a number of sounds by a panel of 23 experts. They each had to rate the annoyance of the sounds by giving it a penalty of either 3 or 6 dB, or zero (no penalty). After modifying the original calculations, a correlation was apparent between the calculated penalty values and the experts' assessments. This yet must be extended to infrasound and tested in field studies.

The literature search yielded two laboratory studies of possible adverse effects typical for infrasound and/or low-frequency sound.
Stevens and Martens (2018) investigated the effect when either identical or somewhat different stimuli are presented to each ear. In the everyday environment sound from a sound source often reaches one ear earlier than the other ear, and at high frequencies, where a sound wave is shorter than the dimensions of the head, this means the ears do not receive quite the same sound at the same time. This is less so for low frequencies, where the wave length is much larger than the head and the difference between the left and right ear is very small. However, the authors suggest that when outdoor sound is audible indoors, due to reflections also at low frequencies the ears do not receive the same sounds. The basis of each stimulus they used in their study was one of three similar sounds with most audible energy at frequencies between 100 and 200 Hz. Each sound could be modulated at either 2, 5 or 10 Hz; that is, the sound varied in strength in a rhythm of 2, 5 or 10 times per second. Then the sound was presented through one loudspeaker at each side of the participant in three combinations: 1) the basic, unmodulated sound at both ears; 2) the modulated sound at both ears; and 3) the unmodulated sounds at one ear and the modulated one at the other. On average the 21 participants rated incoherent sound (stimulus 3) as most

annoying. Also, the annoyance was higher when the modulation frequency (at one of the ears) was 2 Hz, when compared to 5 and 10 Hz. The authors remark that these results are in line with earlier studies which showed that greater differences between the ears create a sense of spaciousness and this is usually experienced as unpleasant.

In a Finnish report, not yet published in a scientific journal, Maijala et al (2020) describe a survey, sound measurements and laboratory experiments that were set up in order to investigate the role of infrasound in health complaints related to wind farms. 70 out of 1351 survey respondents (5%) reported symptoms they attributed to infrasound from a wind farm. On average these 'symptomatic respondents' lived closer to a wind farm than those without symptoms. For these respondents a number of factors were significantly associated with their symptoms: having chronic diseases, being annoyed by different aspects of wind turbines and considering wind turbines as a health risk. Of all respondents, 10% considered WT infrasound a high risk to their personal health; 18% considered it as a high risk to health in general. The sound measurements were performed in two uninhabited countryside dwellings at 1.5 km from a wind farm. From the measurements it was concluded that in these dwellings the infrasound levels were like levels occurring typically in an urban environment. The highest levels were at 0.1 to 1 Hz, but at these extreme low frequencies the levels were well below the hearing threshold. Recordings with the highest infrasound and amplitude modulation levels were selected for the laboratory experiments. The results of these experiments were: 1) those that had reported WT (infra)sound related symptoms did not exhibit an increased sensitivity for WT infrasound; 2) total WT sound level and amplitude modulation were a cause for increased annoyance, not infrasound; 3) WT infrasound or WT sound annoyance had no association with heart rate or heart rate variability, nor with skin conductance (as physiological measures of stress).

In the report of Krahé et al (2020), already mentioned in 4.1, participants were submitted to several physiological tests during exposure. Tests involved blood pressure, heart rate and EEG. Tests showed no differences between the different exposures and no differences between predisposed participants and others.

4.3 Sub-audible including vestibular effects

In our 2017 review we concluded that residential levels of infrasound from wind turbines are not strong enough to affect the sense of balance. Also, at the present levels of wind turbine sound, the occurrence of syndromes (not medically accepted as diagnosis) vibroacoustic disease (VAD) or the 'visceral vibratory vestibular disease' (VVVD) causing the wind turbine syndrome (WTS) is unproven and unlikely. However, symptoms associated with WT sound could result from stress, possibly in relation to the presence of a wind farm. In recent years no studies were published that support the existence of VAD or the VVVD.

Jurado and Marquardt (2020b) investigated the effect of airborne infrasound on the vestibular system. They used a clinical method to assess the functioning of the vestibular system by measuring the electric potential related to muscle contraction (EMG). Earlier research has shown that the vestibular system can be activated by a loud mid- to high-frequency sound. In response to this a muscle in the neck and a muscle attached to the eye contract and this can be measured by EMG. In clinical practice loud clicks are used, either from 6 millisecond sound bursts every 0.2 second (= a repetition rate of 5 Hz) or a continuous loud tone modulated at 40 Hz. To these clinically used stimuli three low-frequency stimuli were added: a continuous sound over 120 seconds with a frequency of either 5, 16 or 40 Hz. All these sounds were presented to 15 normal-hearing participants and to each ear separately, all at levels corresponding to loud sounds. Only the electromyogenic (EMG) reaction to vertical acceleration of the head was measured, not a reaction to horizontal acceleration or rotation of the head. The results showed that the 500 Hz sounds (as used in clinical tests) were significantly related to an EMG response for most participants. There was no significant response in one of both ears for five participants when using sound bursts, for four participants using modulated sound and in both ears for one participant (modulated sound). In contrast, at the low frequencies the response was predominantly not significant. At 4 Hz there was no significant response at all, at 16 and 40 Hz only in four of the 15 participants (of which one with both ears). The authors doubt that that infrasound can produce accelerations of the head at lower sound levels, such as occurring near wind turbines.

Lubner et al (2020) searched the scientific literature for audio-vestibular symptoms after exposure to sound (and electromagnetic energy) and concluded that symptoms were largely reported in small studies, but either not found in larger studies or not studied at all. They also conclude that symptoms were mostly studied after self-reported exposure, and data on the situation before exposure was not available.

In the report of Krahé et al (2020), mentioned in 4.1 and 4.2, participants were also submitted to several neurological tests during exposure. All tests concerned the sense of balance and included keeping balance, performing targeted movements, the occurrence of nystagmus (repetitive, uncontrolled eye movement) and eye fixation. Tests showed no differences between the different sound exposure scenarios and no differences between predisposed participants and others.

4.4 Effect of Vibrations

In our 2017 review there was little information about the perception of vibrations from wind turbines; the only post-2000 study then available (Cooper, 2014) suggested that some residents appeared to experience sensations in relation to the wind turbine operation that could be related to vibrations. We speculated that perhaps the rhythmic character of wind turbine sound could lead to vibrations of a house and thus wind turbine operation could be perceived indirectly inside a house.
Takahashi (2017) investigated if very low-frequency/infrasound could be experienced as a vibration of the head or body. He exposed four normal-hearing participants to six infrasound and low-frequency tones from 16 to 50 Hz in an office type setting. By varying the sound level for each frequency, the hearing threshold was determined, as well as the levels where the sound started to be ‘slightly annoying’, ‘very annoying’ or ‘too

loud to work'. Apart from this, the levels were determined where the sound became unpleasant (unpleasant threshold) and where the participants felt a 'vibration in the head' (vibration threshold). The results show that the level where participants felt a vibration in the head was on average about 6 dB (at 16 Hz) to 15 dB (40 Hz) above their average hearing threshold. This vibration threshold almost coincided with levels at which the sound started to be slightly annoying. The threshold above which the sound was rated as unpleasant was still higher and was close to levels at which the sound started to be 'too loud to work'. Takahashi investigated the perception of vibration in the body and head when exposed to low-frequency sound in earlier studies. In a study with 14 participants (Takahashi, 2013) he also found that the threshold for vibration in the head was higher than the threshold of hearing when participants were exposed to low-frequency sounds of 16 to 50 Hz. Because the threshold was the same as the threshold for 'vibration in the body', he concluded that the head was the most sensitive part of the body to feel vibrations from infrasound. In the 2013 study he also determined the threshold for perceived vibration when participants wore ear mufflers that reduced the sound level at the ear by 15 dB at 16 Hz, increasing to 25 dB at 80 Hz. There was no difference in vibration threshold at the lowest frequency of 16 Hz between wearing ear mufflers or not. At higher frequencies the threshold for vibration perception was up to about 10 dB higher when ear mufflers were worn. Based on his experiments Takahashi hypothesizes that it is the sound pressure on the eardrum and the resulting signal in the hearing system that leads to the sensation of vibration. He states that the effect of ear mufflers does not contradict this, although it is not a matter of simply reducing the sound pressure in the ear canal.

Krahé et al (2020) asked participants to rate their perception of vibration, pressure and unease when exposed to each one of four infrasounds or silence (see description in section 4.1). All were perceived mainly in the head area (head, brain, ears), much less in other body parts. This applied to every sound scenario, including silence. Due to a sometimes low response and unequal numbers of participants, no conclusion could be drawn about the significance of differences between exposure scenarios (including silence).

Nguyen et al (2020) performed measurements of vibrations in three houses at relatively large distances (houses 1, 2 and 3 at 2.4, 3.3 and 5 km) from a wind farm. Vibrations of the floor (in house 2) and the bed frame (house 1) were weak and related to the wind around the house. In contrast, vibrations on the window (house 3) included the amplitude modulation of the wind farm sound and were correlated to the wind farm. The wind turbine related sound levels inside these houses was below the average hearing threshold for all frequencies below about 50 Hz, infrasound levels with at least 30 dB.

5 Conclusions

5.1 Conclusions from chapter 3

Conclusions about the health effects of wind turbine sound have not fundamentally changed since our 2017 review. In general, an association is found between the sound level due to wind turbines and annoyance. Also, an association with sleep disturbance is considered plausible, even though a direct relation is still uncertain because of the limited number of studies and the sometimes contradictory results. In general, the evidence is stronger for self-reported sleep effects than objective sleep indicators.

The evidence reviews on annoyance, sleep, cardiovascular and metabolic effects and cognition and mental health for the WHO (Guski et al, 2017) (Basner and McGuire, 2018) (van Kempen et al, 2018) (Clark and Paunovic, 2018) included wind turbine sound. Together with some high-quality reviews and updates, the earlier conclusions have now a more solid base. The number, study size and quality of the evidence on annoyance and sleep disturbance do justify the carrying-out of a meta-analysis. It is recommended to distinguish hereby between objective and subjective sleep indicators. Also, for a range of clinical outcomes and outcomes on mental health, evidence is increasing, but the number of studies is still too limited to perform such a meta-analysis.

Since 2017 several studies have been published on the association between WT sound and cardiovascular effects such as ischaemic heart disease, stroke, and medication use for hypertension. No significant effects were found. An exception is the so-called Danish Nurse cohort study, which reports, as worded by the authors “suggestive evidence” for an association between long-term exposure to WT sound and atrial fibrillation amongst female nurses. Possibly the fibrillation is a consequence of (chronic) annoyance, although in the same cohort no association with stroke or ischemic heart disease was found.

The review on annoyance, sleep disturbance, cardiovascular and metabolic health outcomes (van Kamp et al, 2020a) yielded two studies investigating the association between wind turbine sound and the incidence of diabetes. Neither study found an association between WT sound and self-reported or diagnosed diabetes. There is also no evidence of an association between WT sound and obesity.

For mental health and quality of life there is insufficient evidence for a direct relation with wind turbine sound level. Cognitive effects have not been studied in relation to WT sound. For neither low birth weight nor cancer significant associations were found with WT sound.

Despite limited evidence, an exposure-effect relation was developed for WT sound in the WHO Guidelines (WHO, 2018), and the related limit values were conditional. The current “Environmental Noise Guidelines for the European Region” recommends that wind turbine noise levels should be limited to 45 dB (Lden), based on a 10% prevalence of being highly annoyed (WHO, 2018). The World Health Organization further notes that noise exposure from an environmental source like a wind turbine may be reduced through simple measures like insulating windows or building barriers (WHO, 2018). Meta-analysis based on the evidence since 2014 allows for deriving a more solid EER for annoyance and for sleep.

The general exposure-effect relation for annoyance from wind turbine sound includes all aspects that influence annoyance and thus averages over all local situations. The relation can therefore form an indication only of the annoyance levels to be expected in a local situation. One study shows that this relation can also be used for the more recent larger (3 to 5 MW) turbines. In an endeavour to develop a composite annoyance measures which includes annoyance with factors other than noise Michaud et al (2018b) have shown the complexity of annoyance due to wind turbines. Freiberg et al (2019) recommend that studies should account for these complex pathways of annoyance as an outcome parameter – that is influenced by different moderator variables – or as a mediator variable for other health outcomes. A composite measure of multiple WT related exposures is a promising way to go ahead.

Without pretending to be exhaustive, noise sensitivity, attitude towards wind turbines, visual aspects and economic benefit come again forward as the most important mediators and moderators.

From epidemiological studies and experiments the typical character of wind turbine sound again came forward as one of the key issues. Especially the rhythmic character of the sound (technically: Amplitude Modulation or AM) is experienced as annoying and described as a swishing or whooshing sound. Residential wind turbine sound levels themselves are modest when compared to those from other sources such as road traffic or industrial noise. But at equal sound levels, sound from wind turbines is experienced as more annoying than that of other sources. This is confirmed again in recent studies(e.g. Klaeboe, 2016). Acoustic analysis in one new study identified amplitude-modulated noise as a major cause of the complaints. In general, the conclusion is still supported that annoyance increases with amplitude modulation, but AM is not an unequivocal causal factor. Several new experiments showed that AM was a strong predictor of response (in terms of annoyance) in combination with visual aspects. The combined effect of the two is worthwhile studying further in larger groups and outside the laboratory.

Some studies investigated the effect of landscape evaluation and other visual aspects. Chronic annoyance from these physical factors, and from noise, is assumed to be related to stress, and there is enough evidence that stress can negatively affect people's health and well-being. However, there is no evidence for a direct association between visual aspects of WTs and health effects. Several studies have more extensively evaluated the determining factors of acceptance. Participation in the decision-making process, co-ownership (literal and symbolic), consumption of local energy come forward as important pull factors.

Overall it is concluded that people are more willing to accept new turbines in their vicinity if they can participate in decision making, the turbines are owned by a group of citizens, and if the generated electricity is consumed in the region instead of being exported and in general experience a sense of control. This is in line with conclusions about the role of these factors in mitigating the aversive effects of other sources such as aircraft sound (Ansensio et al, 2017) (Lercher et al 2017) (Haubrich, 2020). Health is often used in the debates around WT farms, but facts brought forward about health effects are often contradictory.

5.2 Conclusions from chapter 4

Recent studies largely confirm the results of our earlier review: the perception of infrasound and low frequency sound is generally in agreement with what we know from literature and there is no indication that infrasound well below the hearing threshold can have any effect on humans.

Except for one study, the studies published since 2017 show that infrasound and low frequency sound is processed in the auditory cortex where also normal sound is processed. Moreover, hearing thresholds based on brain activity agree with those based on ‘classical’ psycho-acoustics. The brain studies also show that infrasound and very low frequency sound increase very steeply in loudness when compared with normal sound, which again is known from ‘classical’ psycho-acoustics. A new insight is that individually perceived loudness correlates better with brain activity than with the level of the sound. Perhaps this is related to noise sensitivity, where a highly sensitive person perceives a certain sound level as louder than a less sensitive person does.

One study (Weichenberger et al, 2017) suggests that a sub-audible infrasound of 12 Hz is associated with brain activity. It is unclear what effect this brain activity can have elsewhere in the brain or body. The authors take a big leap when speculating that this could be linked to physiological as well as psychological health effects. In our opinion we first need to be sure this is a true effect of an inaudible sound. The stimulus was just 2 dB below the hearing threshold and perhaps it was, during the prolonged exposure, so close to audibility that it could stimulate the brain. The authors suggest that participants were “constantly left guessing, whether stimulation actually occurred or not when near-threshold infrasound was presented” (Weichenberger et al, 2017). This ‘guessing’ did not occur (no concurring brain activity) when no sound was presented. They suggest that if the outer hair cells indeed react to sub-audible sound, as mentioned by Salt and Hullar (2010), this could explain the concurring brain activity. An alternative explanation may be that the brain activity was there because the near-threshold infrasound was just, perhaps intermittently, audible. If so, it may be hard for the brain to recognize or evaluate the sound due to the very low audibility, which may explain the activity in the amygdala and anterior cingulate cortex (ACC) reported by Weichenberger et al (2017). These brain areas are known to be involved in auditory processing (superior temporal gyrus) and tinnitus perception (ACC) (Vanneste and De Ridder, 2012). The ACC relates to areas implicated in affective processing, such as the amygdala (Stevens et al, 2011). Whatever the explanation, the brain activity occurred near the audibility threshold and not at lower levels further away from the threshold. This would be necessary for wind farm infrasound to have an effect. Our conclusion is that it is necessary to study brain activation from infrasound at levels comparable to those near wind turbines/farms and with more realistic sounds before concluding that inaudible infrasound can have an effect on residents.

If normal sound is present, it may be harder to detect soft infrasound compared to situations where only the soft infrasound is present. In contrast, the presence of infrasound appears not to have an effect on the detection threshold of normal sound. However, infrasound may influence the perception of normal sound: a tone of 63 or 125 Hz together with 8 Hz infrasound is similar to our ears to a 63/125 Hz tone with a variation in strength at a rate of 8 Hz. We need more research to find out if these interactions between infrasound and normal sound occur over a wider frequency range and not just the artificial sounds used in laboratory settings. If that would be the case, the implications are 1) that the threshold at which the human ear can detect wind turbine infrasound may be raised because of the presence of the normal WT sound and 2) that the infrasound peak at the blade passing frequency (and its harmonics) may in principle be perceived as a modulation of the normal sound coming from a wind turbine or the environment. In practice the perceived ‘added modulation’ is probably less pronounced than the modulation of the wind turbine sound that is already present in conditions where the infrasound peak is present.

The recent studies of possible effects of audible infrasound and low frequency sound confirm earlier results. When persons, including those complaining about WT infrasound, are exposed to WT sound including infrasound, the total WT sound level and amplitude modulation may be a cause for increased annoyance, not infrasound. Also, WT infrasound had no effect on physiological measures of stress, such as changes in heart rate or heart rate variability, or skin conductance. Soft or inaudible infrasound or very low frequency sound does not lead to a reaction of the vestibular system, at least not the part that detects vertical acceleration. When exposed to infrasound or very low frequency sound, a vibration in the body or head is felt at sound levels close to or higher than the hearing threshold. At similar or higher levels, the sound is rated as less pleasant, either because of its loudness or the added vibration or both. A low frequency sound was also found to be less pleasant when the sound at one ear differs somewhat from the sound at the other ear. This is, for low frequency sound, more likely to occur indoors than outdoors. Finally, vibrations measured in dwellings at relatively large distances from a wind farm (2.4 to 5 km) were of low level and unlikely to cause adverse effects. The vibration of a window pane was related to the airborne sound of the wind farm, the vibrations of a floor and bed frame were more likely to be caused by wind around the house.

This leads to the conclusion that low-frequency sound is part of the total sound of wind turbines and has the same effects audio sound has: it can be annoying and may have effects on (getting to) sleep and, if chronic, this may lead to further health effects. This is also true for other sound sources such as road, rail or air traffic. Because of the low attenuation, low-frequency sound becomes relatively more important at larger distances and inside dwellings. Infrasound is attenuated even less, but coming from wind turbines and at typical distances to residences it is too weak for human perception.

5.3 End conclusion

The level of wind turbine sound is modest when compared to other sources such as transportation (road, rail and air traffic) or industry. Studies show that in practice sound levels are usually less than 45 dBA. Nevertheless, at equal sound levels, sound from wind turbines is experienced as more annoying than that of many other sources.

Based on current knowledge about the effect of WT sound on health we can conclude that living near a WT or hearing sound of wind turbines can lead to chronic annoyance among residents. For other health effects such as sleep disturbance, insomnia, mental health effects there is no consistent evidence. The new evidence confirms earlier conclusions about the influence of the low-frequency component of WT sound and infrasound from wind turbines: there is no indication that it has other effects on residents than normal sound has or that infrasound well below the hearing threshold can have any effect. When people are exposed to WT sound (over all frequencies), the level and amplitude modulation of all WT sound are the main cause for increased annoyance, rather than low frequency sound or infrasound.

There is evidence that sleep disturbance is associated with annoyance rather than to WT sound above a certain level. Also, new evidence shows an association between total annoyance and health complaints, but we cannot draw conclusions about the direction of this relationship: do people highly annoyed by WT sound have more health complaints or are people with health complaints more annoyed by WT sound. Nevertheless, chronic annoyance itself can lead to a feeling that the quality of the living environment has deteriorated or will do so in the future. This can have a negative impact on well-being and health of people living in the vicinity of wind turbines. The moderate effect of wind turbine sound on annoyance and the range of factors predicting the levels of annoyance implies that reducing the impact of wind turbine sound will profit from considering other aspects associated with annoyance as well. The influence of these factors is not necessarily unique for wind turbines. Important factors include noise sensitivity, attitudes towards WTs, health concerns, visual aspects and aspects related to the procedure preceding the building of a wind park. The role of factors such as participation in the planning process, procedural justice, feelings of fairness and balance of costs and benefits from wind turbines are even more strongly supported by current evidence. In summary: the health complaints are primarily associated with a range of non-acoustic factors rather than the actual exposure levels.

Acknowledgements

This review was financed by the Noise and NIR Division of the Swiss Federal Office for the Environment (Bundesamt für Umwelt). We gratefully acknowledge the contributions of Floor Boekelman, Rob van Spronsen and Sietske Staatsen, Joost Gorter and Kim White to the preparation of this review. We also would like to thank Judith Hin and Marjolein 't Hoen for reviewing this manuscript.

References

Ansensio, César, Gasco Sanchez, Luis, Arcas, G.(2017) A Review of Non-Acoustic Measures to Handle Community Response to Noise around Airports, Current Pollution Reports 3(3):230–244.
Bakker, R. H., Pedersen, E., van den Berg, G. P., Stewart, R. E., Lok, W., & Bouma, J. (2012). Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress. Science of the total environment, 425, 42-51.
Baliatsas, C., Kamp, I. van, Bolte, J., Schipper, M., Yzermans, J., Lebret, E.(2012) Non-specific physical symptoms and electromagnetic field exposure in the general population: can we get more specific? A systematic review. Environment International: 2012, 41(1), 15-28
Basner, M. and S. McGuire (2018). "WHO environmental noise guidelines for the european region: A systematic review on environmental noise and effects on sleep." International Journal of Environmental Research and Public Health 15(3).
Behler and Uhlenkamp (2020): Behler, O. and S. Uppenkamp (2020). "Activation in human auditory cortex in relation to the loudness and unpleasantness of low-frequency and infrasound stimuli." PLoS ONE 15(2).
Beuret, JE. (2016). Is trust negotiable? Building a place-based general interest for the acceptance of the Saint Brieuc and Saint Nazaire offshore wind farms. Geographie Economie Societe, 2016; 18(3):335-58.
Botelho A, Arezes P, Bernardo C, Dias H, Pinto LMC (2017) Effect of Wind Farm Noise on Local Residents' Decision to Adopt Mitigation Measures Int J Environ Res Public Health. 2017 Jul 11;14(7).
Bräuner, E. V., Jørgensen, J. T., Duun-Henriksen, A. K., Backalarz, C., Laursen, J. E., Pedersen, T. H., ... & Andersen, Z. J. (2018). Long-term wind turbine noise exposure and incidence of myocardial infarction in the Danish nurse cohort. Environment international, 121, 794-802.
Bräuner, E. V., Jørgensen, J. T., Duun-Henriksen, A. K., Backalarz, C., Laursen, J. E., Pedersen, T. H., ... & Andersen, Z. J. (2019a). Long-term wind turbine noise exposure and the risk of incident atrial fibrillation in the Danish Nurse cohort. Environment international, 130, 104915.
Bräuner, E. V., Jørgensen, J. T., Duun-Henriksen, A. K., Backalarz, C., Laursen, J. E., Pedersen, T. H., ... & Andersen, Z. J. (2019b). Association Between Long-Term Exposure to Wind Turbine Noise and the Risk of Stroke: Data From the Danish Nurse Cohort. Journal of the American Heart Association, 8(14), e013157.
Brennan, N., Van Rensburg, T.M. & Morris, C. (2017). Public acceptance of large-scale wind energy generation for export from Ireland to the UK: evidence from Ireland. Journal of Environmental Planning and Management, 60:11, 1967-1992.
Burke, E., Hensel, J., Fedtke, T., Uppenkamp, S., & Koch, C. (2019). Detection Thresholds for Combined Infrasound and Audio-Frequency Stimuli. Acta Acustica united with Acustica, 105(6), 1173-1182.
Carlile S., Davy J.L., Hillman D., Burgemeister K. (2018). A Review of the Possible Perceptual and Physiological Effects of Wind Turbine Noise. Trends in Hearing, 23.

Clark C., Crumpler C., Notley H (2020) Evidence for environmental noise effects on health for the United Kingdom policy context: A systematic review of the effects of environmental noise on mental health, wellbeing, quality of life, cancer, dementia, birth, reproductive outcomes, and cognition International Journal of Environmental Research and Public Health (2020) 17:2 Article Number: 393.

Clark, C. and K. Paunovic (2018). "Who environmental noise guidelines for the European region: A systematic review on environmental noise and quality of life, wellbeing and mental health." International Journal of Environmental Research and Public Health 15(11).

Clark, S. and L. C. Botterill (2018). "Contesting facts about wind farms in Australia and the legitimacy of adverse health effects." Health (London, England : 1997) 22(4): 337-355.

Cooper, S (2014): The results of an acoustic testing program Cape Bridgewater wind farm. The Acoustic Group, report 44.5100.R7:MSC, 2014

Delicado, A., Truninger, M., Figueiredo, E., Silva, L. & Horta, A. (2017). A Blot on the landscape: Consensus and Controversies on Wind Farms in Rural Portugal. Emerald Publishing Limited, 2017; 179-195.

EARS Communiqué (2015). Ears Project Communiqué: Assessment and safety of non-audible sound. June 2015

Frantál, B., Van Der Horst, D., Kunc, J., Jaňurová, M. (2017). Landscape disruption or just a lack of economic benefits? Exploring factors behind the negative perceptions of wind turbines. Journal of Landscape Ecology, 15(2):139-47.

Freiberg, A., Schefter, C., Girbig, M., Murta, V. C., & Seidler, A. (2019). Health effects of wind turbines on humans in residential settings: Results of a scoping review. Environmental research, 169, 446-463.

Freiberg, A., Schefter, C., Hegewald, J. & Seidler, A. (2019). The influence of wind turbine visibility on the health of local residents: a systematic review. Int Arch Occup Environ Health 92, 609–628.

Gölz, S. & Wedderhoff, O. (2018). Explaining regional acceptance of the German energy transition by including trust in stakeholders and perception of fairness as socio-institutional factors. Energy Research and Social Science, 43: 96-108.

Grima Murcia, M.D., Sanchez Ferrer, F., Sorinas, J., Ferrandez, J.M. & Fernandez, E. J. (2017). Application of electroencephalographic techniques to the study of visual impact of renewable energies. Journal of Environmental Management, 2017 Sep 15;200:484-9.

Guski, Rainer Dirk Schreckenberg and Rudolf Schuemer (2017) WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Annoyance Int. J. Environ. Res. Public Health 2017, 14(12), 1539; https://doi.org/10.3390/ijerph14121539 - 08 Dec 2017

Haac, T. R., Kaliski, K., Landis, M., Hoen, B., Rand, J., Firestone, J., ... & Pohl, J. (2019). Wind turbine audibility and noise annoyance in a national US survey: individual perception and influencing factors. The Journal of the Acoustical Society of America, 146(2), 1124-1141..

Haubrich, Julia Narcisa E. Burtea Paul Hooper Rebecca Hudson Dan Radulescu Fiona Raje Dirk Schreckenberg (2020) Foundations for a comprehensive approach of acoustic and non-acoustic measures of aircraft noise annoyance mitigation Aerospace Europe conference, Bordeaux, France.

Hongisto V, Oliva D, Keranen J (2017) Indoor noise annoyance due to 3-5 megawatt wind turbines-An exposure-response relationship. J Acoust Soc Am. 2017 Oct;142(4):2185.

Hübner, G., Pohl, J., Hoen, B., Firestone, J., Rand, J., Elliott, D., & Haac, R. (2019). Monitoring annoyance and stress effects of wind turbines on nearby residents: A comparison of US and European samples. Environment international, 132, 105090.ISO/TS 15666:2003(en) Acoustics — Assessment of noise annoyance by means of social and socio-acoustic surveys https://www.iso.org/standard/28630.html.

Janhunen, S., Hujala, M. & Pätäri, S. (2018). The acceptability of wind farms: the impact of public participation. Journal of Environmental Policy & Planning, 20:2, 214-235.

Janssen, S.A., Vos, H , Eisser AR, Pedersen E. (2011) A comparison between exposure-response relationships for wind turbine annoyance and annoyance due to other noise sources. J Acoust Soc Am 130(6): 3746-3753.

Jurado C, D Gordillo, BCJ Moore (2019): On the loudness of low-frequency sounds with fluctuating amplitudes. Journal of the Acoustical Society of America, v146 n2 1142-1149.

Jurado and Marquardt (2020b): On the Effectiveness of airborne infrasound in eliciting vestibular-evoked myogenic responses. Jurado C, T Marquardt. Journal of Low Frequency Noise, Vibration and Active Control, v39 n1 3-16.

Jurado, C., & Marquardt, T. (2020a). Brain's Frequency Following Responses to Low-Frequency and Infrasound. Archives of Acoustics, 45(2), 313-319.

Kageyama, T., Yano, T., Kuwano, S., Sueoka, S., & Tachibana, H. (2016). Exposure-response relationship of wind turbine noise with self-reported symptoms of sleep and health problems: A nationwide socioacoustic survey in Japan. Noise & health, 18(81), 53.

Keith, S. E., Feder, K., Voicescu, S. A., Soukhovtsev, V., Denning, A., Tsang, J., ... & van den Berg, F. (2016). Wind turbine sound pressure level calculations at dwellings. The Journal of the Acoustical Society of America, 139(3), 1436-1442.

Kim, H., Cho, S.H. & Song, S. (2018). Wind, power, and the situatedness of community engagement. Public Underst Sci, 28(1):38-52.

Klaeboe R, Sundfor HB. Windmill Noise Annoyance, Visual Aesthetics, and Attitudes towards Renewable Energy Sources. International journal of environmental research and public health. 2016;

Koch (2017): Hearing beyond the limit: Measurement, perception and impact of infrasound and ultrasonic noise. Koch C, M Brink. 12th ICBEN Congress on noise as a public health problem, 2017

Kongprasit, S., Waewsak, J., Chaichana, T. In: Waewsak J, S OT, Gagnon Y, Sangkharak K, editors. (2017). Wind Turbine and Local Acceptance in Southern Thailand C3 - Energy Procedia. Elsevier Ltd, 138: p. 380-5.

Krahe (2019): Proposal of a procedure assessing the annoyance of low-frequency noise and infranoise C3 - INTER-NOISE 2019 MADRID - 48th International Congress and Exhibition on Noise Control Engineering

Krahé D, Alaimo Di Loro A, Müller U, Elmenhorst E, De Gioannis R, Schmitt S, Belke C, Benz S, Großarth S, Schreckenberg D, Eulitz C, Wiercinski B, Möhler U. Lärmwirkungen von Infraschallimmissionen (Noise effects from infrasound immissions). Report Umweltbundesamt (German Environmental Agency), 2020, available at https://www.umweltbundesamt.de/publikationen/laermwirkungen-von-infraschallimmissionen (report in German with English summary)

Krogh, C. M., McMurtry, R. Y., Dumbrille, A., Hughes, D., & Gillis, L. (2020). Preliminary Results: Exploring Why Some Families Living in Proximity to Wind Turbine Facilities Contemplate Vacating Their Homes—A Community-Based Study. Open Access Library Journal, 7, e6118.Lamy, J., Azevedo, I.M.L., de Bruine, W., Morgan, M.G. Perceptions of wind energy projects in two coastal Massachusetts communities. Electricity Journal. 2017;30(7):31-42.

Landeta-Manzano, B., Arana-Landín, G., Calvo, P.M. & Heras-Saizarbitoria, I. (2018). Wind energy and local communities: A manufacturer's efforts to gain acceptance. Energy Policy, 121:314-24.

Lane JD, Bigelow PL, Majowicz SE, McColl RS (2016) Impacts of Industrial Wind Turbine Noise on Sleep Quality: Results From a Field Study of Rural Residents in Ontario, Canada. J Environ Health. 2016 Jul;79(1):8-12.

Langer, K., Decker, T. & Menrad, K. (2017). Public participation in wind energy projects located in Germany: Which form of participation is the key to acceptance? Renewable Energy, 2017;112:63-73.

Langer, K., Decker, T., Roosen, J. & Menrad, K. (2018). Factors influencing citizens' acceptance and non-acceptance of wind energy in Germany. Journal of Cleaner Production, 175:133-44.

Lercher, Peter, Bert De Coensel, Luc Dekonink, and Dick Botteldooren Community Response to Multiple Sound Sources: Integrating Acoustic and Contextual Approaches in the Analysis Int J Environ Res Public Health. 2017 Jun; 14(6): 663. Published online 2017 Jun 20. doi: 10.3390/ijerph14060663 PMID: 28632198

Liebe, U., Bartczak, A.& Meyerhoff, J. (2017). A turbine is not only a turbine: The role of social context and fairness characteristics for the local acceptance of wind power. Energy Policy, 107:300-8.

Lubner RJ , Kondamuri NS , Knoll RM , Ward BK , Littlefield PD , Rodgers D , Abdullah KG , Remenschneider AK , Kozin ED. (2020) Review of Audio vestibular Symptoms Following Exposure to Acoustic and Electromagnetic Energy Outside Conventional Human Hearing. Frontiers in neurology, 11: 234.

Macdonald, C., Glass, J. & Creamer, E. (2017). What Is the Benefit of Community Benefits? Exploring Local Perceptions of the Provision of Community Benefits from a Commercial Wind Energy Project. Scottish Geographical Journal, 2017;133(3-4):172-91.

Maijala P, A Turunen, I Kurki, L Vainio,S Pakarinen, C Kaukinen, K Lukander, P Tiittanen, T Yli-Tuomi, P Taimisto, T Lanki,,K Tiippana, J Virkkala, E Stickler, M Sainio. Infrasound does not explain symptoms related to wind turbines.Report of the Prime Minister's Office, Helsinki 2020

Marquardt and Jurado (2018): Amplitude Modulation May Be Confused with Infrasound. Marquardt T, C Jurado. Acta Acustica united with Acustica, Vol. 104 (2018) 825 – 829

Michaud DS, Keith SE, Feder K, Voicescu SA, Marro L, Than J, et al (2016a) Personal and situational variables associated with wind turbine noise annoyance. The Journal of the Acoustical Society of America. 139:1455-66.
Michaud, D. S., Feder, K., Keith, S. E., Voicescu, S. A., Marro, L., Than, J., ... & Lavigne, E. (2016b). Exposure to wind turbine noise: perceptual responses and reported health effects. The Journal of the Acoustical Society of America, 139(3), 1443-1454.
Michaud DS, Feder K, Keith SE, Voicescu SA, Marro L, Than J, Guay M, Denning A, Murray BJ, Weiss SK, Villeneuve PJ. (2016c) Effects of wind turbine noise on self-reported and objective measures of sleep. Sleep. J1;39(1):97
Michaud, D. S., Feder, K., Voicescu, S. A., Marro, L., Than, J., Guay, M., ... & Villeneuve, P. (2018a). Clarifications on the design and interpretation of conclusions from health Canada’s study on wind turbine noise and health. Acoustics Australia, 46(1), 99-110.
Michaud, D. S., Leonora Marro and James McNamee (2018b). "Derivation and application of a composite annoyance reaction construct based on multiple wind turbine features." Canadian journal of public health = Revue canadienne de sante publique 109(2): 242-251.
Michaud, D. S., Leonora Marro and James McNamee (2018c). "The association between self-reported and objective measures of health and aggregate annoyance scores toward wind turbine installations." Canadian journal of public health = Revue canadienne de sante publique 109(2): 252-260.
Micic, G., Zajamsek, B., Lack, L., Hansen, K., Doolan, C., Hansen, C., ... & Mercer, J. (2018). A review of the potential impacts of wind farm noise on sleep. Acoustics Australia, 46(1), 87-97.
Morsing, Ageborg J., Smith, M. G., Ögren, M., Thorsson, P., Pedersen, E., Forssén, J., & Persson Waye, K. (2018). Wind turbine noise and sleep: Pilot studies on the influence of noise characteristics. International journal of environmental research and public health, 15(11), 2573.
Nguyen, D. P., Hansen, K., & Zajamsek, B. (2020). Human perception of wind farm vibration. Journal of Low Frequency Noise, Vibration and Active Control, 39(1), 17-27.
Pawlaczyk-Łuszczyńska, M., Zaborowski, K., Dudarewicz, A., Zamojska-Daniszewska, M., & Waszkowska, M. (2018). Response to noise emitted by wind farms in people living in nearby areas. International journal of environmental research and public health, 15(8), 1575.
Pedersen, E. (2011) Health aspects associated with wind turbine noise: Results from three field studies. Noise Control Eng. J. 2011, 59, 47–53.
Pohl, J., Gabriel, J., & Hübner, G. (2018). Understanding stress effects of wind turbine noise–The integrated approach. Energy Policy, 112, 119-128.
Poulsen, A. H., Raaschou-Nielsen, O., Peña, A., Hahmann, A. N., Nordsborg, R. B., Ketzel, M., ... & Sørensen, M. (2018a). Long-term exposure to wind turbine noise and redemption of antihypertensive medication: a nationwide cohort study. Environment international, 121, 207-215.
Poulsen, A. H., Raaschou-Nielsen, O., Peña, A., Hahmann, A. N., Nordsborg, R. B., Ketzel, M., ... & Sørensen, M. (2018b). Long-term exposure to wind turbine noise at night and risk for diabetes: a nationwide cohort study. Environmental research, 165, 40-45.
Poulsen, A. H., Raaschou-Nielsen, O., Peña, A., Hahmann, A. N., Nordsborg, R. B., Ketzel, M., ... & Sørensen, M. (2018c). Pregnancy exposure to wind turbine noise and adverse birth outcomes: a nationwide cohort study. Environmental research, 167, 770-775.

Poulsen, A. H., Raaschou-Nielsen, O., Peña, A., Hahmann, A. N., Nordsborg, R. B., Ketzel, M., ... & Sørensen, M. (2019a). Impact of long-term exposure to wind turbine noise on redemption of sleep medication and antidepressants: a nationwide cohort study. Environmental health perspectives, 127(3), 037005.
Poulsen, A. H., Raaschou-Nielsen, O., Peña, A., Hahmann, A. N., Nordsborg, R. B., Ketzel, M., ... & Sørensen, M. (2019b). Long-term exposure to wind turbine noise and risk for myocardial infarction and stroke: a nationwide cohort study. Environmental health perspectives, 2019(3), 037004.
Radun J, Hongisto V, Suokas M. (2019) Variables associated with wind turbine noise annoyance and sleep disturbance. Building and Environment. 150:339-48.
Sæþórsdóttir, A.D., Ólafsdóttir, R., Smith, D. (2018). Turbulent times: tourists' attitudes towards wind turbines in the Southern Highlands in Iceland. International Journal of Sustainable Energy. 2018;37 (9):886-901.
Salt A.N., Hullar T.E., Responses of the ear to low frequency sounds, infrasound and wind turbines. Hearing research. 2010 Sep 1;268(1):12-21.
Schäffer, B., Pieren, R., Schlittmeier, S. J., & Brink, M. (2018). Effects of different spectral shapes and amplitude modulation of broadband noise on annoyance reactions in a controlled listening experiment. International journal of environmental research and public health, 15(5), 1029.
Schäffer, B., Pieren, R., Hayek, U. W., Biver, N., & Grêt-Regamey, A. (2019). Influence of visibility of wind farms on noise annoyance–A laboratory experiment with audio-visual simulations. Landscape and Urban Planning, 186, 67-78.
Scherhaufer, P., Höltinger, S., Salak, B., Schauppenlehner, T. & Schmidt, J. (2018). A participatory integrated assessment of the social acceptance of wind energy. Energy Research and Social Science, 45:164-172.
Scherhaufer, P., Höltinger, S., Salak, B., Schauppenlehner, T. & Schmidt, J. (2017). Patterns of acceptance and non-acceptance within energy landscapes: Acase study on wind energy expansion in Austria. Energy Policy, 109:863-70.
Simos, J., Cantoreggi, N., Christie, D. &Forbat, J. (2018). Wind turbines and health: a review with suggested recommendations. Environnement Risques & Santé, 2018; 18: 1-11
Sklenicka, P. & Zouhar, J. (2018). Predicting the visual impact of onshore wind farms via landscape indices: A method for objectivizing planning and decision processes. Applied Energy, 209:445-54.
Smith M.G., Ögren M., Thorsson P., Hussain-Alkhateeb L., Pedersen E., Forssén J., Ageborg Morsing J., Persson Waye K (2020) A laboratory study on the effects of wind turbine noise on sleep: Results of the polysomnographic WiTNES study. Sleep (2020).
Song K, Di G, Xu Y, Chen X. Community survey on noise impacts induced by 2MW wind turbines in China. Journal of Low Frequency Noise Vibration and Active Control. 2016; 35:279-90.
Sonnberger, M. & Ruddat, M. (2017). Local and socio-political acceptance of wind farms in Germany. Technology in Society, 2017;51:56-65.
Stevens FL , Hurley RA , Taber KH. Stevens et al, 2011: Anterior cingulate cortex: unique role in cognition and emotion. Journal of neuropsychiatry and clinical neurosciences. Spring; 23(2): 121-5.

Stevens and Martens (2018): Stevens, M. and W. L. Martens (2019). The influence of binaural incoherence on annoyance reported for unpleasant low frequency sound C3 - Australian Acoustical Society Annual Conference, AAS 2018, Australian Acoustical Society.
Takahashi, Y. (2013) Vibratory sensation induced by low-frequency noise: The threshold for ``vibration perceived in the head'' in normal-hearing subjects. Journal of Low Frequency Noise Vibration and Active Control 32, no. 1/2, (2013): 1-10, 2013.
Takahashi, Y. (2017): Study on the relationship between unpleasantness and perception of vibration in the head of subjects exposed to low-frequency noise C3 - Takahashi Y. INTER-NOISE 2017 - 46th International Congress and Exposition on Noise Control Engineering
Thomson, H. & Kempton, W. (2018). Perceptions and attitudes of residents living near a wind turbine compared with those living near a coal power plant. Renewable Energy, 123:301-11.
Tonin (2017): A Review of Wind Turbine-Generated Infrasound: Source, Measurement and Effect on Health. Tonin R Acoustics Australia. 2018;46(1):69-86.
van den Berg, F., & van Kamp, I. (2017). Health effects related to wind turbine sound. Commissioned by the Swiss Federal Office for the Environment (FOEN)
Van Den Berg, F., Pedersen, E., Bouma, J., & Bakker, R. (2008). Visual and acoustic impact of wind turbine farms on residents.. Final report.https://www.rug.nl/research/
Van Kamp I, Breugelmans O, Van Poll R, Baliatsas C, Van Kempen E. (2017): Determinants of annoyance from humming sound as indicator of low frequency noise C3 - In: McMinn T, Duncan A, editors. Proceedings of ACOUSTICS 2017 Perth: Sound, Science and Society - 2017
van Kamp, I., & van den Berg, F. (2018). Health effects related to wind turbine sound, including low-frequency sound and infrasound. Acoustics Australia, 46(1), 31-57.
van Kamp, I., Simon, S., Notley, H., Baliatsas, C., & van Kempen, E. (2020a). Evidence Relating to Environmental Noise Exposure and Annoyance, Sleep Disturbance, Cardio-Vascular and Metabolic Health Outcomes in the Context of IGCB (N): A Scoping Review of New Evidence. International journal of environmental research and public health, 17(9), 3016.
van Kamp, I., van Kempen, E. E. M. M., Simon, S. N., & Baliatsas, C. (2020b). Review of Evidence Relating to Environmental Noise Exposure and Annoyance, Sleep Disturbance, Cardio-Vascular and Metabolic Health Outcomes in the Context of the Interdepartmental Group on Costs and Benefits Noise Subject Group (IGCB (N)). RIVM Report 2019-0088; Netherlands.
Van Kempen, E., Casas, M., Pershagen, G., & Foraster, M. (2018). WHO environmental noise guidelines for the European region: a systematic review on environmental noise and cardiovascular and metabolic effects: a summary. International journal of environmental research and public health, 15(2), 379.
Vanneste and De Ridder, 2012: The auditory and non-auditory brain areas involved in tinnitus. An emergent property of multiple parallel overlapping subnetworks. Vanneste S, D De Ridder. Frontiers in Systems Neuroscience, v6 (20120508)

Weichenberger, M., Kühler, R., Bauer, M., Hensel, J., Brühl, R., Ihlenfeld, A., ... & Kühn, S. (2015). Brief bursts of infrasound may improve cognitive function–An fMRI study. Hearing Research, 328, 87-93.
Weichenberger M, Bauer M, Kühler R, Hensel J, Forlim CG, Ihlenfeld A, et (2017): Altered cortical and subcortical connectivity due to infrasound administered near the hearing threshold- Evidence from fMRI. al (2017). PLoS ONE 12(4): e0174420
Wen, C., Dallimer,M., Carver, S. & Ziv, G. (2018). Valuing the visual impact of wind farms: A calculus method for synthesizing choice experiments studies. Total Environ, 1;637-638:58-68.
WHO, 1946. Constitution of the World Health Organization: principles. World Health Organization. ⟨http://www.who.int/about/mission/en/⟩ (accessed 12 September 018).
WHO, Environmental Noise Guidelines for the European Region (2018) WHO, Bonn.
Wüstenhagen, R., M. Wolsink, M.J. Bürer. Social acceptance of renewable energy innovation: An introduction to the concept. Energy policy 35 (5), 2683-2691, 2013
Zaunbrecher, B.S. and M. Ziefle, Integrating acceptance-relevant factors into wind power planning: A discussion. Sustainable Cities and Society, 2016. 27: p. 307-314

Annex 1 Search strategy

Our previous review was based on a systematic literature search over the period 2000 to early 2017. Three databases were searched: Scopus, Medline and Embase. This updated review uses publications from the period 2017 through June 2020. The results of our 2017 review were updated in July 2018, using the exact same search strategy and databases as in 2017. For the second update until 2020 the Medline and Embase databases were not anymore available, or not available in the same form. The platform and search syntax has been changed, so a new search strategy had to be applied. Also, we added the database PsycINFO; it showed that this hardly expanded the references from the other databases.

Because the possible effects of inaudible sound at very low frequencies is an important topic in public wind farm discussions, this topic was added to the literature search.
Again, observational as well as experimental studies described in the peer review literature was performed. Language was restricted to German, English, French and Dutch. The search strategy is described below.

For the main topic, health effects of wind turbine sound, only studies which in the title, abstract or summary mention that the association between the noise of wind turbines and reaction, health or wellbeing was studied were included. Also studies addressing participation during the building process were accepted for review. This implied that the association between exposure to wind turbine (low frequency) noise an annoyance, health, wellbeing or activity disturbance in the adult population was studied. For the low frequency topic, studies mentioning low frequency sound or noise or infrasound in the title together with a reaction, health effect or wellbeing in the title were included.
For a first selection the following criteria were used. Inclusion: papers addressing human health effects, perception, opinion, concern in relation to wind turbines. Exclusion: papers addressing non-human effects such as ecosystem effects, animals, papers about solely technical aspects of the wind turbines, papers regarding health effects of noise but not specific for wind turbines.

The papers were grouped in 7 categories: review, health effects, offshore, low frequency noise, visual aspects, social aspects and not relevant. All reviews and health effects studies were included for full paper examination, offshore studies were a-priori excluded, papers from the other categories were reconsidered after reading the abstracts. Lastly, after full examination of the review and health effect papers by the two authors, a final decision was made about inclusion in this review. As a result 76 new publications were included in the report.

In the context of this report the main results are summarized per outcome. For the key studies, the study design, outcome etc. are discussed in more detail. For this review primarily scientific publications are used, both from peer reviewed journals and conference proceedings.

As usual all material from the selected literature has been read and analysed, but not necessarily included as reference, e.g. because the study was less relevant than originally thought or in case of doubling with other references. (e.g. a conference paper and article from same authors/study).

A.1 Search strategy in Scopus, Medline and Embase databases, until July 2018

This is the same as in our previous review (van den Berg & van Kamp, 2017; Van Kamp&van den Berg, 2018)

A.2 Search strategy in Scopus, July 2018-July 2020

Topic: health effects of wind turbine sound
TITLE ("wind turbine*" OR "windmill*" OR "windmill*" OR "windfarm*" OR "wind farm*" OR "windpark*" OR "wind park*" OR "windenerg*" OR "wind energ*"))
AND
(TITLE ("health effect*" OR "health risk*" OR "stress" OR "annoy*" OR "health impact*" OR "sleep" OR "noise avoid*" OR "noise abat*" OR "preval*" OR "inciden*" OR "adverse" OR "human health*" OR "avers*" OR "attitud*" OR "percept*" OR "perceiv*" OR "quality of life" OR "well being" OR "wellbeing" OR "concern*" OR "emot*" OR "accept*"))
AND PUBYEAR > 2017
Topic: low frequency effects
TITLE("infrasound*" OR "low frequency nois*" OR "low frequency sound*" OR "infrasonic*" OR "low frequency thresh*" OR "audibi*")
AND
(TITLE("health effect*" OR "risk*" OR "stress" OR "annoy*" OR "health impact*" OR "sleep" OR "noise avoid*" OR "noise abat*" OR "preval*" OR "inciden*" OR "adverse" OR "human health*" OR "avers*" OR "attitud*" OR "percept*" OR "perceiv*" OR "quality of life" OR "well being" OR "wellbeing" OR "concern*" OR "emot*" OR "accept*"))
AND PUBYEAR > 2017

A.3 Search strategy in Embase, July 2018-July 2020

Topics: health effects of wind turbine sound and low frequency effects
#1. 'wind turbine'/exp OR 'wind farm'/exp OR 'wind turbine*':ti,ab OR 'wind farm*':ti,ab OR 'wind power'/exp
#2. 'low frequency noise'/exp OR (low:ti AND frequency:ti AND ('noise*':ti OR 'signal*':ti OR ‘noise':ti,ab OR 'low frequency sound':ti,ab OR 'low frequency ultrasound':ti,ab OR 'low frequency signal*':ti,ab OR 'low frequency thresh*':ti,ab OR 'infrasound'/exp OR 'infraso*':ti OR 'audability':ti,ab OR 'audibl*':ti
#3. 'noise'/exp/mj OR 'nois*':ti OR 'noise pollution'/exp/mj
#4. 'hearing'/exp/mj
#5. 'sound'/exp/mj OR 'sound*':ti
#6. 'annoyance'/exp OR 'annoy*':ti
#7. 'wellbeing'/exp OR 'health*':ti OR 'health'/exp OR 'health status'/exp OR 'wellbeing*':ti
#8. 'aversion*':ti OR 'stress*':ti OR 'complain*':ti OR 'distress*':ti OR 'disturb*':ti OR 'worries':ti OR (('sensiti*' NEAR/3 noise):ti) OR 'sound pressure level*':ti OR 'sleep disturbance*':ti OR 'sleep quality':ti OR 'stress'/exp OR 'cognitive*':ti OR 'aversion'/exp OR 'distress

syndrome'/exp OR 'sleep quality'/exp OR 'perception*':ti OR 'unpleasant*':ti
#9. 'quality of life'/exp OR ('quality':ti AND ('life':ti OR living:ti))
#10. #2 OR #3 OR #4 OR #5 OR #6 OR #7 OR #8 OR #9
#11. #6 OR #7 OR #8 OR #9
#12. #1 AND #10
#13. #1 AND #10 AND [2017-2020]/py
#14. #1 AND #10 AND [2017-2020]/py AND ([dutch]/lim OR [english]/lim OR [french]/lim OR [german]/lim)
#15. #2 AND #11 NOT #1
#16. #2 AND #11 NOT #1 AND [2017-2020]/py
##17. #2 AND #11 NOT #1 AND [2017-2020]/py AND ([dutch]/lim OR [english]/lim OR [french]/lim OR [german]/lim)

A.4 Search strategy in Psycinfo, Januari 2017-July 2020

Topic: health effects of wind turbine sound
(("health effect*" or "risk*" or "stress*" or "annoy*" or "health impact*" or "sleep*" or "noise avoid*" or "noise abat*" or "preval*" or "inciden*" or "adverse" or "human health*" or "avers*" or "attitud*" or "percept*" or "perceiv*" or "quality of life" or "well being" or "wellbeing" or "concern*" or "emot*" or "accept*" or "commun*" or "engag*" or "activis*" or "prefer*").m_titl.)
and
(("wind turbine*" or "wind farm*" or "wind park*" or "windfarm*" or "windpark*" or "windmill*" or "wind mill*" or "wind energ*" or "windenerg*").m_titl.)
Topic: low frequency effects
("health effect*" or "risk*" or "stress" or "annoy*" or "health impact*" or "sleep*" or "noise avoid*" or "noise abat*" or "preval*" or "inciden*" or "adverse" or "human health*" or "avers*" or "attitud*" or "percept*" or "perceiv*" or "quality of life" or "well being" or "wellbeing" or "concern*" or "emot*" or "accept*" or "commun*" or "engag*" or "activis*" or "prefer*").m_titl.
and
("infrasound*" or "low frequency nois*" or "low frequency sound*" or "infrasonic*" or "low frequency thresh*" or "audibi").m_titl.

A.5 Inclusion and exclusion criteria

Include when:
• paper concerns (all aspects of) sound from wind turbines;
• and: paper concerns a (qualitative or quantitative) study; no restriction regarding study design
• and: at least some link is made with health effects and/or (social) wellbeing (including annoyance, community response);
• and: language is English, French, German or Dutch.

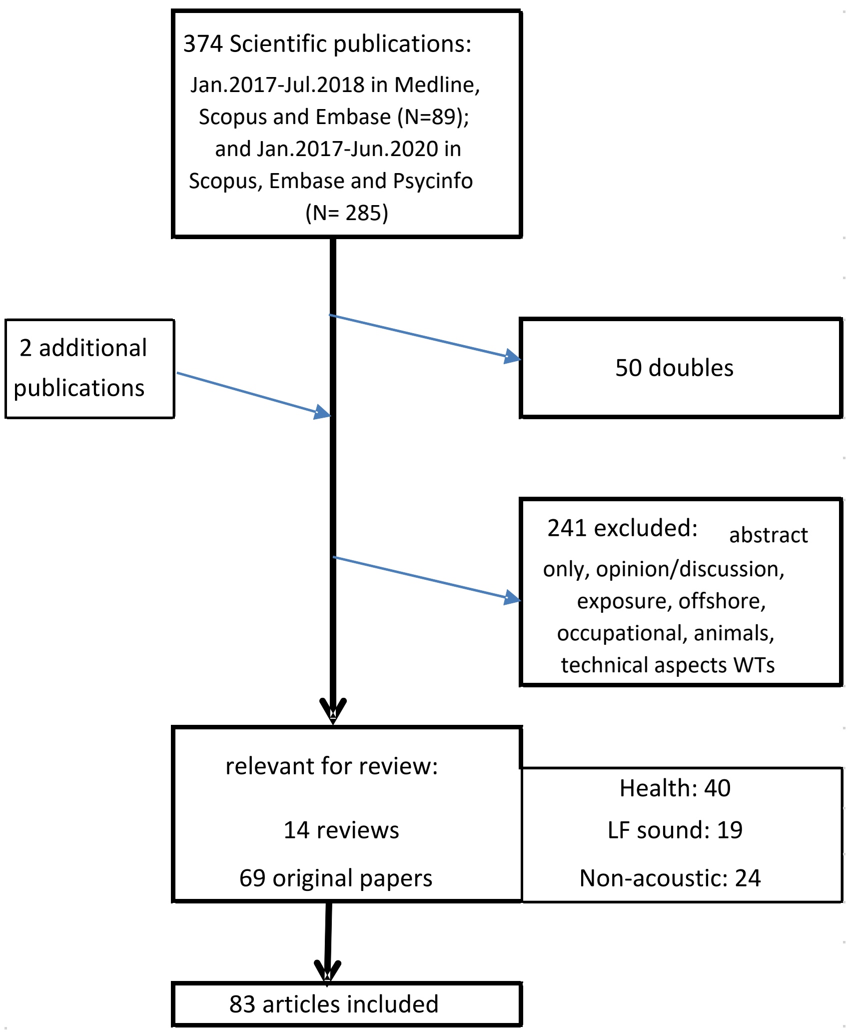
Exclude when:
• paper concerns occupational health and safety; offshore; effects on others than residents;
• or: paper is a commentary, editorial or opinion, letter to editor; errata or discussion between people.

With respect to non-acoustic effects:

Include when one or more of the following issues are addressed:
- Visual aspects:
    - impact on landscape, movement horizon pollution, etc
    - light effects; shadow flicker
- Safety
- Vibration
- Electromagnetic fields
- Contextual and personal factors (noise sensitivity, attitude , effect of participation, co-ownership)

A.6 Search results

As the diagram below shows, the literature searches yielded 324 (374 – 50) publications of which 76 are included in the review and reference list.



Annex 2: Glossary

ACC	Anterior cingulate cortex
AM	Amplitude Modulation
Atrial fibrillation	Irregular and often rapid heart rate
BMI	Body Mass Index
CI	Confidence interval
CNHS	Canadian Noise and Health study
Cross-sectional	A study at one specific point in time
CTL	Community Tolerance Level
DALY	Disability-adjusted life year
dB	deciBel, a measure for the level of sound
dBA	A-weighted deciBel, corrected for human hearing
DEFRA	U.K. Department for Environment, Food & Rural Affairs
EEG	Electroencephalography
EER	Exposure Effect Relation
EMG	Electromyography
Et al	denotes the co-authors of a publication
EU	European Union
FFR	Frequency Following Response
(%)HA	(percentage) Highly annoyed people
(%)HSD	(percentage) Highly Sleep Disturbed people
IHD	Ischeamic Heart Disease
Incidence	Measure of the probability of occurrence of a given (medical) condition in a population within a specific period of time
L_{den}	Day-evening-night equivalent sound level
L_{Aeq}	A-weighted equivalent sound pressure level averaged over a period of time
L_{night}	Nighttime equivalent sound level
MW	MegaWatt (million Watt)
NAS	Noise Annoyance Stress
NS	Noise sensitivity
OR	Odds ratio
Polysomnography	A test used to diagnose sleep disorders.
Prevalence	Actual number of cases of disease or injury present in a population at any particular moment in time
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
REM	Rapid eye movement (sleep stage)
SD	Standard deviation
SPL	Sound Pressure Level: the actual sound level in certain conditions or at a certain time
VAD	Vibroacoustic disease
VVVD	Visceral vibratory vestibular disease
WHO	World Health Organization
WT	Wind Turbine
WTA	Willingness to Accept
WTP	Willingness to pay

RIVM

Committed to *health and sustainability* -