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Towards explaining the positive effect of vegetation on the perception of environmental noise☆

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ABSTRACT

Audio-visual interactions play a significant role when humans perceive the environment. In this review paper, it is analysed how visible vegetation can be used to mitigate negative environmental noise perception with a focus on noise annoyance. Existing research has been analysed in view of three potentially explaining mechanisms namely source (in)visibility, the mere presence of visible green, and vegetation as a source of natural sounds. The source concealing potential vegetation has cannot fully explain reported findings. The restorative properties of visible vegetation seems the dominant mechanism. Visible natural features of good quality lead to sustained attention restoration and stress relief, counteracting negative outcomes of endured environmental noise exposure. There is strong evidence that noise annoyance experienced at home largely decreases when outdoor nature is present in the window pane. Additional support regarding the importance of such micro-restorative experiences is found by research at the working place, in hospital environments and at schools. Non-directly visible neighbourhood green shows to be positive as well, but with a smaller impact on noise perception. Natural sounds and especially bird songs are relaxing on theirselves, and support the restorative action of nature by suggesting nearby and vital nature. Based on rough quantitative estimates, the equivalent level reduction of (high quality) visible green from home could reach 10 dBA. This equivalent level reduction comes on top of the physical sound pressure level reduction one might obtain behind vegetation belts. At higher exposure levels, the improved noise perception one can get from vegetation is larger than at lower levels. The bulk of literature is concerned with road traffic noise, although scarce research suggests the applicability is much broader. Personal characteristics are expected to play a role in the interaction between noise perception and vegetation too.

1. Introduction

Traditionally, noise pollution abatement efficiency is judged by the reduction in sound pressure level. However, noise annoyance, one of major health impacts (see e.g. Fritschi et al., 2011), is not only linked to physical noise indicators. Based on surveys, typically only 30% of the variance in self-reported noise annoyance can be assigned to the sound pressure level. Noise annoyance is the result of complex cognitive processes, and is influenced by a myriad of acoustical, environmental and personal factors (see e.g. Stansfeld et al., 1993; Lercher, 1996; Brambilla et al., 2013).

Audio-visual interactions play a significant role when humans perceive the environment, which is essentially a multi-sensorial process. At the higher levels in the nervous system, the various inputs are merged. Information from some senses can be neglected or suppressed in favour of information from others, possibly leading to different reactions. Southworth (1969) showed that when auditory and visual settings are coupled, attention to the visual stimulus reduced the conscious perception of sound, and vice versa. Consequently, such knowledge could potentially be used to mitigate a negative noise perception. Visible vegetation takes an important place in this respect and is the subject of this review.

Laymen often consider vegetation separating a sound source and a receiver as an effective means against noise, although this is often not supported by measured sound pressure level reductions. Even dense and thick hedgerows (Van Renterghem et al., 2014) or a single row of

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trees (Jang et al., 2015) perform poorly in reducing decibels from road traffic. Perfater (1979) reported that "a significant number of respondents indicated that vegetation was a viable alternative to noise walls", and that "it was claimed that their experience with vegetation supported this contention". It was found by Yang et al. (2011) that 90% of the subjects believed that landscape plants contribute to noise reduction and 55% overrated the plants' actual ability to attenuate noise. Another example (Aletta et al., 2018) comes from a survey along a bicycle track on an embankment, bordering a major ring road, with a high amount of visible vegetation and with measured equivalent sound pressure levels exceeding 70 dBA. Strikingly, 45% of the respondents rated this environment as "calm" (as opposed to "busy", forced choice between two extremes). In addition, there are numerous cases where the sudden removal of a single row of trees bordering a road (e.g. due to maintenance/safety reasons) lead to a strong increase in noise complaints at nearby dwellers. Such an action is not accompanied by (measured) sound pressure level increases, putting road administrators at a loss what to do (Het Nieuwsblad, 2015).

A plausible reason for the preceding findings is that the distinction between physical noise reduction and perception related effects is not made by the public at large. In their overall assessment of e.g. loudness or self-reported noise annoyance, perception effects are implicitly accounted for and – to some extent – translated to apparent (physical) noise level reduction. These findings point at a strong and positive effect of vegetation on how environmental noise is perceived.

In this literature review, the main aim is to assess the relative importance of three potentially explaining mechanisms for the improved noise perception in the presence of vegetation. These are related to the (in)visibility of the sound source, the effect of the mere presence of vegetation (directly visible or nearby), and vegetation acting as a source of natural sounds. Note that source (in)visibility, visual aesthetics and "positive" sounds have been (separately) recognized as important factors related to environmental sounds and noise perception. Vegetation has the unique ability to combine all of these.

2. Method

This thematic literature review mainly aims at revealing the underlying mechanisms of the (positive) effect of vegetation on noise perception. Firstly, quite obvious and rather broad search terms were entered in the Web of Science search engine such as "(noise OR sound) AND (perception OR annoyance OR loudness) AND (vegetation OR green)". Secondly, most relevant papers ("key studies") were identified and categorized based on their focus on one of the three aforementioned potentially explaining mechanisms. If available, more in-depth explanations already provided in these papers were used in a third step to start the search for explaining mechanisms. A much wider search was added here, often going back to the fundamentals of human listening and hearing, and how environments are perceived. Possible explanations were consequently evaluated with the other key studies in mind to see if these can be generalized. Evidence from related disciplines have been included to further strengthen findings. A summary of plausible mechanisms is then provided. By "snowballing", references cited in the papers found were further explored. Recent environmental noise conference proceedings have been searched as well to ensure including up-to-date research.

In the discussion section, a reanalysis has been made of specific studies (sometimes with contradictory findings as a result of focussing on one specific mechanism) in view of all potentially explaining mechanisms considered. Overall, this allowed to weigh them up against each other and to reveal the dominant mechanisms when optimizing environmental noise perception. In addition, where possible, rough quantitative estimates have been made of the operating effects. Although it was not specifically searched for, there is a main interest in road traffic noise in most cited articles.

Various perception related indicators are found in literature dealing with the interaction between vegetation and noise perception. Examples are loudness (e.g. Aylor and Marks, 1976), pleasantness (e.g. Viollon et al., 2002; Echevarria-Sanchez et al., 2017a,b), relaxing potential (e.g. Viollon et al., 2002), noisiness (e.g. Watts et al., 1999) and tranquillity (e.g. Pheasant et al., 2008; Watts et al., 2011). Only considering literature specifically assessing self-reported noise annoyance would limit this review to a rather small number of studies. Although there is not always a one-on-one relationship, these alternative perception indicators are – at least to some extent – linked (Berglund et al., 1976). In general, a more tranquil, relaxing or pleasant environment, or a less noisy one, is expected to be less annoying. The link between loudness and self-reported noise annoyance has been explicitly assessed and confirmed, except at very low levels (Berglund et al., 1990).

3. Sound source (in)visibility

3.1. Key studies

A number of studies specifically focussed on source visibility in relation to vegetation. Watts et al. (1999) found that in 2 out of 4 in-situ experiments, noisiness decreased (for a given sound pressure level) with less visual screening of road vehicles (provided by a small vegetation belt). In the two other cases, foliage transparency (ranging from 20% to 90%) did not have a significant influence on the noisiness rating. By changing distance relative to the belts, ratings by the participants were made over a wide range of noise levels (from 55 till 85 dBA).

In the study by Sun et al. (2018), 4 combinations of projected window views (videos) in a mock-up living room were put to the test: green-invisible road, green-visible road, no green-visible road, no green-invisible road. The test persons were asked to rate their noise annoyance over the past 10 minutes. Statistical analysis allowed to separate the factors source visibility and the presence of vegetation. It was concluded that only source visibility was a statistically significant factor in a basic analysis, with visible road traffic leading to less annoyance. Exposure levels ranged from 45 till 60 dBA, measured in the centre of the living room.

Zhang et al. (2003) studied the noise annoyance perceived by persons facing a road bordering a park, either in front (road vehicles visible) or behind a 2-m high hedge (from which the road could not be seen). Vision on the source (in front of the hedge) lead to higher self-reported annoyance. Levels ranged from 60 to 70 dBA.

3.2. Mechanisms

The aforementioned experiments point in different directions; the effect of source visibility on environmental noise perception seems complex. In related literature, two competing mechanisms can be identified, indicated here as *audio-visual congruency* and *attention focussing*.

The congruency hypothesis means that the combination of the auditory and visual stimulus should make sense – if not, this gives rise to a salient mental image and a potentially negative reaction. A source that can be easily heard should also be seen, while visual screening without sufficient noise reduction conflicts with expectations. More fundamentally, this effect can be explained by the fact that during the course of evolution, hearing developed as an organ for perceiving and responding to danger (Westman and Walter, 1981). There is a direct connection between the inner ear and "fight or flight" neural mechanisms via the autonomic nervous system (Westman and Walter, 1981). This primitive function still exists in humans nowadays and also (common) environmental noise induces such reactions. In this view, a reasonably loud noise event, not supported by a corresponding or plausible visual stimulus, could be perceived as an undefined threat. Anticipation becomes difficult in such a situation and could lead to a more negative reaction compared to when the sound source is clearly visible. The experiment by Watts et al. (1999) and Sun et al. (2018) support this congruency hypothesis. Somewhat related, Viollon et al. (2002) found that natural sounds with co-occurring natural scenes are rated as more pleasant than when offered in an urban visual setting. In parks, the more sounds are congruent with the expectations, the less is the evoked annoyance (Brambilla and Maffei, 2006). Ge and Hokao (2005) found that the sound of transportation is more disliked in a natural landscape since less congruent. Aylor and Marks (1976) refers to a "loudness-barrier" effect (translated here to: "You should see what you (clearly) hear"), similar to the "size-weight" illusion ("What is small is expected not to be heavy").

In contrast, an additional visual stimulus on top of the auditory stimulus might give rise to more attention being paid towards the noise source. Two major processes in the human brain, namely vision and audition, are dealing with the same object – the sound source. The experiment by Zhang et al. (2003) supports this hypothesis. This concept is well-known in the field of speech intelligibility: numerous clinical and laboratory studies showed that combined auditory-visual perception is superior to perception through either audition or vision alone (Erber, 1975). In case of unwanted sounds, support by a visual stimulus could lead to a stronger reaction. Cox (2008) found that in the extreme case of "horrible" sounds, like finger nails scraping down a blackboard or dentist drills, also presenting the associated image made the perception of such sounds even worse. Another well known example in this respect is noise annoyance by wind turbines. Wind turbines are tall and highly visible structures, most often placed in open areas. It was found that this aspect contributes largely to the fact that wind turbines are rated much more negatively than would be expected purely based on their noise levels (see e.g. Pedersen and Larsman, 2008).

Both hypotheses are nicely reconciliated in Aylor and Marks's (1976) experiment where a loudspeaker was positioned behind various types of (visual) barriers. As long as the source could be seen, reduced visibility was accompanied by a reduction in apparent loudness, consistent with the attention focussing hypothesis. However, in case of a fully (visually) obscured source this effect reversed: the loudness was overestimated – the sound was perceived surprisingly loud by the participants due to the audio-visual incongruency. The lowest perceived loudness for a given (objective) sound pressure level was found for the visual semi-transparent barrier (i.e. the "fence" in Aylor and Marks's study (1976)) at intermediate levels. It is here hypothesized that such a case is a compromise between the above described mechanisms. Also vegetation can be easily designed as semi-transparent.

In this respect, the virtual reality study reported by Maffei et al. (2013) is of interest. Both opaque and fully (visually) transparent noise walls were presented to a test panel during playback of exactly the same audio fragments of a passing train. The transparent noise wall was rated as less loud and lead to less self-reported noise annoyance. This is particularly interesting as such a setting with a clearly visible sound source might have poor expectations regarding the noise shielding since people generally expect audio-visual congruency. This is confirmed by the experiments conducted by Joynt and Kang (2010) after testing various visual appearances of noise barriers and asking specifically for preconceptions at the respondents. In addition, full attention was drawn to the sound source for the transparent barrier in Maffei et al. (2013). Yet, levels are experienced (surprisingly) low and this lead to an overreaction which turned out to be positive. So it can be concluded that the lack of congruency does not seem to be an issue when the sound pressure level is low. The other way around, namely clearly hearing a source without seeing it, is much more problematic.

The discrepancy between the experimental results reported by Watts et al. (1999) and Sun et al. (2018), opposed to Zhang et al. (2003), primarily focussing on visual shielding of road traffic by vegetation, indicates that other effects than source (in)visibility come into play when looking at interactions between sound and natural landscapes.

4. Restorative effect of vegetation

Many studies reported a strong effect of visuals on auditory judgement, without considering source (in)visibility as a potentially explaining factor. Especially visual scenes containing vegetation and natural elements seem to have a positive effect on the appreciation of the sound environment. A number of key studies in this respect are discussed below.

4.1. Key studies

Viollon et al. (2002) found that with an increasing degree of urbanization in the visual stimulus, all but human sounds were perceived as less pleasant or more stressful (as opposed to pleasant/relaxing). In their experiment, urbanization is defined as opposed to natural landscapes. This holds for both congruent and incongruent audio-visuals. Technical sounds like road traffic noise are thus perceived as more pleasant or relaxing in a greener environment. These effects, although in general statistically significant, were rather small with a difference in the rating scale not exceeding 1 unit (on a 1-to-7 scale). Sound levels of the stimuli ranged from 57 to 64 dBA each lasting for 20 s, and sound sources were not visible in their tests.

The tranquillity rating (TR) (Pheasant et al., 2008; Watts et al., 2011) was proposed as a landscape management planning tool. The environmental property "tranquil" is applicable to settings that are "quiet, peaceful, and that are good places to get away from everyday life". TR is negatively correlated with the overall noise level. Interestingly, there is a positive and quite important correction dependent on the fraction of visible natural elements: such elements increase the perceived tranquillity independent of the sound level in their formulation. The relevance of the number of natural elements is also stressed by Cervinka et al. (2016), studying the perceived restorativeness of one's own garden.

In their quiet side study, Gidlöf-Gunnarsson and Öhrström (2010) found that courtyard quality lead to a significant decrease in self-reported noise annoyance. Courtyard attractiveness/quality was defined as a combination of "naturalness" and "utilization" value. Those who had a high quality courtyard had a chance of 16% and 29% for at least moderate annoyance (for level categories, at the most exposed side, of 58-62 and 63-68 dBA, respectively). For low-quality courtyards, these chances increased to 27% and 42%. Given the interest in locations with dominant road traffic noise at the most exposed side and since this was a quiet side study, the sound sources were presumably not visible at the quiet sides, which is a necessary condition to have significant physical noise shielding by the building itself.

Bodin et al. (2015) assessed the presence of a quiet side in their postal survey both directly and indirectly, the latter by asking if there was a window facing a natural environment ("a yard, garden, water or green space"). The overall proportion annoyed due to traffic noise, experiencing poor sleep quality or concentration problems was lower in the group having access to a quiet side, irrespective of the way of assessing its presence. The adjusted odds ratio for noise annoyance was 0.47 (95% confidence interval ranging from 0.38 to 0.59). The discrimination between visual green at either the loud or quiet side could not be made; an overall positive effect is found here.

Three studies (Li et al., 2010; Van Renterghem and Botteldooren, 2016; Leung et al., 2017) focussed on the effect of the landscape, as actually seen from within the dwelling, on long-term integrated self-reported noise annoyance at home, by far the most natural way of assessing this important health outcome.

Outdoor vegetation as seen from the living room's window, facing a busy inner-city ring road, showed to be a strong predictor of self-reported noise annoyance (Van Renterghem and Botteldooren, 2016). The absence of view on vegetation resulted in a 34% chance of being at least moderately annoyed by (road traffic) noise, while this chance reduced to 8% for respondents answering to have a pronounced vegetation view. Only actual vision on outdoor vegetation lead to statistical significance (at the 5% level); living room (indoor) plants and the mere presence of vegetation in the neighbourhood (i.e. visible and invisible vegetation as seen from the living room) were found to be insufficient to lead to a statistical significant finding. All dwellings considered had a quiet side, however, with an unreported (visual) quality. Interestingly, all respondents had full vision on at least one complete driving direction along this ring road. The dwellings under study were European style closed-row buildings, directly bordering the ring road, so at rather close distance from the road vehicles. The strong effect seen here could thus not be linked to a source (in)visibility effect.

Li et al. (2010) held surveys showing that visible greenery is able to reduce noise annoyance for residents of high-rise buildings overlooking urban parks and wetlands. The visual category "a lot of greenery, parks and gardens" lead to a shift towards less annoyance of 2 points on an eleven-point noise annoyance scale, compared to "no greenery". In this study, source (road) visibility was not controlled for, and could differ among participants. Given that the high-rise building blocks under study were surrounded by highways, it is assumed that most could see the sound sources, possibly at a rather long distance.

Another study conducted in Hong Kong by Leung et al. (2017) assessed the effect of vision from high-rise buildings on combinations of environmental features. The probability of high annoyance (as opposed to the medium and low annoyance category) in case of views on noise walls was 26%, while vision on greenery yielded only 5%. The baseline probability of high annoyance (regardless of the view) was 16%. Also visible water features could help in reducing the perceived noise annoyance, but slightly less strongly than greenery does. Water features, in contrast to greenery, showed statistically significant interaction effects with other visual environmental features.

4.2. Mechanisms

Environmental psychology already showed decades ago that direct and indirect exposure to nature positively affects humans. Two main explaining frameworks have been developed namely attention restoration theory (ART) (Kaplan and Kaplan, 1989; Kaplan, 1995) and stress recovery theory (SRT) (Ulrich, 1983; Ulrich et al., 1991).

ART states that direct/sustained attention can be restored after fatigue by contact with nature. This replenishment occurs by means of effortless attention, for which a visual scene needs to have four components, indicated by the acronym FACE as used in Payne (2013). A first one is fascination: the visual stimulus is able to keep the focus without the need for direct attention. Many natural features have the property of so-called "soft" fascination: they can effortlessly capture attention in an "undramatic fashion" (Kaplan and Kaplan, 1989). Secondly, the stimulus should provoke a feeling of "being away" from the present situation, allowing the tired cognitive processes to rest (Kaplan and Kaplan, 1989). To complete, the person's own needs or state of mind should be compatible with the landscape and the natural environment should provide a feeling of extent ("immersive"). Natural scenes were found to meet these criteria better than other environments (Kaplan and Kaplan, 1989).

The stress recovery theory (SRT) states that exposure to natural environments could lead to recovery after psychological and physiological arousal. This restorative response is seen as a direct result of the positive affective response (and consequently preference) people have for natural settings. This human feature is often explained as a remnant of our species' evolution in natural environments – (unthreatening) natural content is likely to be associated with access to water, food and shelter and thus vital for survival. Its presence has a soothing function and leads to stress reduction. Similarly, Kaplan and Kaplan (1989) state that a preferred landscape is one where a person can imagine to function in.

The link between the restorative action of exposure to natural features and improved noise perception can be made in a next step. The additional stress caused by exposure to environmental noise (Westman and Walter, 1981) could be mitigated by the stress reducing potential of visible natural elements. In addition, the processing of environmental sounds, occurring spontaneously, may occupy parts of the workload of the human brain. It is known that in a noisy environment it becomes more difficult for people to concentrate on a specific task (Stansfeld et al., 1993; Hygge et al., 1998). Attention restoration may be helpful for "clearing the head" and "preventing residual bits and pieces of cognitive leftovers running around and starting the new task with something of a deficit" (Kaplan and Kaplan, 1989). This is especially true for road traffic noise heard at home, which has no useful (warning) function. In addition, noise annoyance and perception are often linked to the general appreciation of the living environment (see e.g. Botteldooren et al., 2011). Compared to other environments, natural ones are generally experienced as aesthetic (linked e.g. to the level of complexity, pattern, depth, texture, …) and thus preferred (Kaplan and Kaplan, 1989).

EEG data measured from respondents hearing very similar road traffic noise recordings at relatively high levels in either a (visual) traffic scene or park environment were remarkably different (Yang et al., 2011). When being virtually present in the park environment (using video glasses, 3-min experiment at 68 dBA), there were higher alpha and lower beta wave activities, indicating a positively perceived emotional difference. Such objective measurements of brain activity pattern nicely illustrate the assumptions made in previous paragraphs.

5. Vegetation as a source of natural sounds

Vegetative features of sufficient size can be a source of natural sounds, either by attracting or functioning as a habitat for living organisms producing sounds (e.g. bird songs/calls) or by making sounds inherent to their structure (e.g. rustling of leaves). A third group of natural sounds that received quite some attention, often present in an environment containing vegetation, are water sounds.

5.1. Bird songs

In the studies by Yang and Kang (2015) and Hong and Jeon (2013), bird sounds were ranked at the top of the desired natural sounds in an urban environment. Similarly, among the 22 natural sounds the participants listened to (no visuals), the top-3 sounds providing a positive feeling were bird sounds (Krzywicka and Byrka, 2017). In high quality courtyards, bird sounds were more often identified by the respondents than in low quality ones (Gidlöf-Gunnarsson and Öhrström, 2010). In the experiment conducted by Viollon et al. (2002), bird songs strongly outperformed the other sounds regarding their pleasantness/relaxation potential. Also in an urbanized visual setting, bird songs are still rated as (very) positive, but less positive than in a more matching natural environment. Similar to (technical) sound source congruency, also natural sounds are preferably congruent. With increasing bird song loudness, the naturalness and the pleasantness of the soundscape was found to increase, while annoyance decreased (Hao et al., 2015). Calmness of urban green spaces increased when hearing bird songs, and a high importance was placed on the richness of bird species (Hedblom et al., 2017). Based on their in-depth interviews, Ratcliffe et al. (2013) concluded that bird songs and calls are the most salient source of restorative sounds in natural environments people came up with after imagined stress and attention fatigue.

Nevertheless, birds seem quite sensitive to road traffic noise levels, although literature on this topic is very scarce. A long-term experiment with a "phantom road" (i.e. a line array of loudspeakers producing road traffic noise) (McClure et al., 2013) near cherry shrubs showed that both the number of birds observed and species diversity was reduced during the source-on period (leading to an equivalent sound pressure level of 55 dBA, compared to 44 dBA during the source-off period). The total number of birds was reduced with 28% due to the traffic noise. The decline in the number of birds encountered was strongly dependent on species. Some species completely avoided the test location during the noise-on period.

5.2. Wind-induced vegetation noise

Wind-induced vegetation noise occurs at leafed/leafless deciduous trees and coniferous trees, increasing with wind speed (Fegeant, 1999a; Fegeant, 1999b, Bolin, 2009). Leaves make sound resulting from structural vibrations induced by the unsteady contacts with neighbouring elements. This occurs typically near sound frequencies of 3–5 kHz (Fegeant, 1999a). Needles, in contrast, generate noise in an aero-acoustical way producing aeolian tones, whose frequency is dependent on the needle diameter (pine at 1 kHz, spruce at 1.5 kHz, at 6 m/s, see Fegeant (1999a)). These sound frequencies are of high relevance for environmental noise (e.g. rolling noise from road vehicles). Lower sound frequencies are generated as well by mechanically induced vibrations from collisions between branches and twigs and by dipole sources resulting from vortex shedding when the wind flows around them (Bolin, 2009). In leafless deciduous trees, wind speeds near the canopy are larger than when in leaf, making the lower frequency part of the spectrum more relevant (Bolin, 2009).

Given that wind-induced vegetation noise has a rather broad spectrum and that maxima appear at highly audible sound frequencies, energetic masking seems possible. Bolin et al. (2010) showed that this occurs at a signal-to-noise ratio at detection threshold near −10 dB to mask wind turbine sound with wind-induced vegetation noise. When the masker was highway noise and the maskee wind turbine noise (Van Renterghem et al., 2013), this detection threshold strongly reduced to −25 dBA. Consequently, wind-induced vegetation sounds seem rather efficient to fulfil this specific task. Note, however, that both wind-induced vegetation noise and wind turbine sound are of an aerodynamic nature, yielding some resemblance in their spectra, making energetic masking more efficient.

5.3. Water sounds

Water sounds as a potential positive contribution to the soundscape received quite some attention. Galbrun and Ali (2013) reported, based on measurements near various types of water sounds (waterfalls, cascades, fountains, jets and streams), that there is a general lack of low frequency content in such sounds, except for waterfalls at large flow rates. Perceptual assessments probing for peacefulness and relaxation (in gardens and park environments) showed that water sounds should not be less than 3 dB below the road traffic noise level to optimize these indicators (Galbrun and Ali, 2013), confirming previous research (Jeon et al., 2010; You et al., 2010). Similarly, Nilsson et al. (2010) concluded that fountain sounds added to the quality of a city park soundscape by reducing the loudness of (unwanted) road traffic noise. However, to achieve this effect, the water sounds had to be at least 10 dB higher than the road traffic noise – so only close to the water feature, positive effects could be found. Watts et al. (2009) concluded that water sounds are important visual natural features improving self-reported tranquillity. Also the sound of raindrops falling on leaves, often identified and used as "relaxing" sounds, can be mentioned in this respect.

5.4. Mechanisms

The positive effect of the aforementioned natural sounds could potentially be explained by either energetic or informational masking (Leek et al., 1991) of unwanted (technical) sounds. Bird songs and most water sounds lack low frequencies, suggesting poor energetic masking of most technical sounds. Wind-induced vegetation noise has a broader spectrum and could have some masking potential at higher wind speeds, but studies where road traffic noise is the maskee are lacking.

Bird songs seem quite powerful in providing informational masking. This is e.g. confirmed by detailed auditory attention models using bird chirps and bird chorus (Oldoni et al., 2013): already at a signal-to-noise ratio of −10 dB, an urban soundscape largely dominated by road traffic noise starts to benefit from bird sounds when evaluating its pleasantness.

The dynamics of sounds play an important role in their appreciation. The 1/f-dependence of pitch and pressure fluctuation over time in sound signals is seen as a critical balance between predictability (as opposed to chaotic) and novelty (as opposed to boring) (Voss and Clarke, 1975). Such optimal dependency is found in music (Voss and Clarke, 1975). Theoretical considerations in De Coensel et al. (2003) led to the conclusion that 1/f-behaviour is expected as well in natural sounds like bird songs and wind noise. This could allow for prolonged attention capturing and music-likeness, in contrast to most technical sounds.

In addition to these purely auditory effect, the positive action can also be explained by the fact that they support or enhance the restorative action of nature. Natural sounds signify an actually living or vital environment (Ratcliffe et al., 2013): this could support the impression that a person could function well in such an environment compared to silent (or dead) nature. Secondly, natural sounds could increase the feeling of the presence of (nearby) nature, even when not directly visible. In this respect, Kaplan and Kaplan (1989) mention the "thereness": the knowledge that one could enjoy such a natural area is in itself a source of satisfaction. When asking people to communicate their auditory experience of e.g. raindrops falling on leaves or rustling of leaves, this is spontaneously done by gestures (like rapidly shaking of hands and fingers) (Lemaitre et al., 2017). This auditory-visual correspondence shows that such sounds allow to easily visualize natural scenes in the mind. Thirdly, Viollon et al. (2002) discuss the importance of involvement of the listener. Especially bird songs do not implicate subjects directly by demanding or even allowing an active role in production of such sounds. This could strengthen their relaxing and attention restoration potential.

This is further consistent with the findings from Pheasant et al. (2008), Alvarsson et al. (2010) and Krzywicka and Byrka (2017). They found that natural sounds on theirselves (without visual stimuli) are already relaxing and have restoring potential. Alvarsson et al. (2010) found that after episodes of psychological stress, physiological recovery of sympathetic activation is faster during exposure to pleasantly rated nature sounds (in their study a combination of fountains and tweeting birds) compared to road traffic noise or backyards with sounds from air-conditioning units. Similarly, the tranquillity rating was shown to increase with perceived loudness of “biological” sounds, while it decreased for mechanical and human sounds (Pheasant et al., 2008). The top rated natural sounds in Krzywicka and Byrka (2017) were assessed by participants to have stronger restorative qualities than the top rated urban sounds.

Preis et al. (2015) further stress the importance of sounds: natural and positively appreciated soundscapes are able to improve the overall comfort ratings of lower rated visuals. The other way around did not work: adding highly appreciated (deaf) visuals to the less preferred (blind) soundscapes did not improve the self-reported comfort.

6. Discussion

6.1. Visible green through the window vs. nearby green

Research by Li et al. (2010), Van Renterghem and Botteldooren (2016), and Leung et al. (2017) stresses the importance of actual vision on green through the dwelling’s window to reduce noise annoyance at home. In the study by Van Renterghem and Botteldooren (2016), both self-reported visible and neighbourhood green were asked for. The self-reported amount of neighbourhood green showed to be insufficient to significantly affect the self-reported (long-term) noise annoyance, while visible green from the living room window did. Clearly, nearby green contains both visible and not directly visible green. Note, however, that in this study the number of participants was rather low and only strong effects would consequently come out at the 5% significance level given the inherent large variation in perception studies.

In the courtyard attractiveness study (Gidlöf-Gunnarsson and Öhrström, 2010), it can be reasonably expected that almost all dwellings had vision on how the courtyard was landscaped. Note that the relative effects (attractive vs non-attractive) found here are somewhat less pronounced, probably because the presence of green in the courtyard comes on top of the positive effect on noise annoyance of simply having a quiet side. Note that in Van Renterghem and Botteldooren (2016), the amount of vegetation was only assessed at the window overlooking the loud side of a dwelling, while in Gidlöf-Gunnarsson and Öhrström (2010) only the visual appearance of the quiet side was controlled for.

In the study of Gidlöf-Gunnarsson and Öhrström (2007) it was found that the degree of perceived availability to nearby green areas resulted in a decrease in long-term noise annoyance at home and noise disturbance during staying outdoors. Nearby green encourages walking and exercising in the neighbourhood and hearing natural (and human) sounds more often. These effects increase general health and well-being, on top of stress reduction and attention restoration experienced while actually being in the nature near the dwelling. However, the influence was less strong than in Van Renterghem and Botteldooren (2016) and Leung et al. (2017), indicating that its potential does not seem to be fully exploited when the green is not visible from home.

Although people in their homes do not constantly stare through the windows, Kaplan (2001) stresses the importance of the so-called micro-restoration they provide. Accumulating from many short episodes, the view from the window can provide long-term contact with the natural environment, important for sustained restoration. Ulrich (2002) wrote that viewing settings with plants or other nature for only a few minutes can promote measurable restoration even in hospital patients who are acutely stressed. In addition, nature benefits were considered to be remarkably resistant to habituation (Kaplan, 2001). Kaplan (2001) further states that the miniaturization and the “framing” a window provides might help to increase the feeling of extent; the restrained view offering only a glimpse encourages the imagination, strengthening distraction. The importance of window view is further stressed by Cooper-Marcus and Sarkissian (1986), concluding that the primary basis for judgments of the attractiveness of one’s neighbourhood is what can be seen from the window at home. Greener neighbourhoods lead to greater happiness, fully mediated by neighbourhood satisfaction, on its turn fully mediated by greenness of the view from the living room (Van Herzele and de Vries, 2012).

Additional support on the importance of nature in window view is convincingly found at the working place, in hospital environments and at schools. Ulrich (1984) found in his landmark study that patients in hospital rooms overlooking a park recovered faster (i.e. shorter stays at the hospital and less painkiller consumption) from the same surgery than those whose windows faced a brick wall. A related study showed that bedroom view to natural surroundings leads to better improvement in self-reported physical/mental health, although the degree of change varied with gender and diagnostic group (Raanaas et al., 2012). Mcsweeney et al. (2015) defined the term indoor nature exposure (INE) as a health-promotion framework. Watts et al. (2016) found that natural views in wall art in hospital waiting rooms improve tranquillity, aid relaxation and reduce anxiety.

Gilchrist et al. (2015) found that views of green space through the window promotes employee wellbeing. Higher job satisfaction and self-ratings of work performance was found by Lottrup et al. (2015) when window views were dominated by trees or park-like environments. Shin (2007) showed a direct effect of forest views, increasing job satisfaction and reduced job stress. Chang and Chen (2005) recorded the effects of window views and indoor plants in the workplace by electromyography, electroencephalography, blood volume pulse and state-anxiety level. Participants were least nervous or anxious when seeing nature in combination with indoor plants.

Matsuoka (2010) found consistent positive associations between classroom window views with greater quantities of trees and shrubs, and standardized test scores and graduation rates. Li and Sullivan (2016) showed that window views to green landscapes promote high school students’ attention restoration and recovery from stress which was not achieved by only allowing daylight entering the window. Viewing peaceful natural environments from the classroom was found to result in higher end-of-semester grades compared to a view of a concrete retaining wall (Benfield et al., 2015).

6.2. Does positive perception of visual green depend on the noise level?

Following the commonly used dose-effect relationships developed by Miedema and Oudshoorn (2001), the percentage of people annoyed by road traffic noise, but also the uncertainty on such predictions, increases with exposure level. Such curves are intended to estimate the overall noise annoyance in a population, but do not allow accounting for non-acoustical factors explicitly. Implicitly, such effects are included and the confidence intervals are an indication that near the higher levels additional factors have a larger influence. In Van Renterghem and Botteldooren (2016) (L_{den} more or less constant at 73 dBA) and Leung et al. (2017) (CRTN predicted levels between 63 and 65 dBA), a remarkably similar decrease (with a factor of roughly 5) in the percentage at least moderately or highly annoyed respondents was found (in Leung et al. (2017), this concerns the “barrier” visual scenario opposed to the “green” scenario). The study by Gidlöf-Gunnarsson and Öhrström (2010) focusing on the look of the quiet courtyards, so clearly having a much lower sound pressure level, showed a reduction in the chance of at least moderate annoyance smaller than 2. Also here, there is support for the fact that at higher levels, positive effects are somewhat more pronounced. Note, however, that the green effect comes on top of the quiet side benefit so the magnitude of these effects cannot be directly compared.

Overall, it can be reasonably expected that in the higher sound pressure level range, vision on green has a stronger effect than at low road traffic noise levels. Nevertheless, significant positive effects are to be expected over a wide range of environmental sound pressure levels.

The source visibility studies in relation to green further evidence that audio-visual interactions are larger at high sound pressure levels. In the experiment of Aylor and Marks (1976), the influence of the visual setting was strongest near roughly 75 dB. At the extremes (40 dB and 90 dB), however, the visuals did not affect loudness judgement anymore. Zhang et al. (2003) found that hiding the source was more beneficial at 70 dBA than at 60 dBA. Hong and Jeon (2014) reported that the impact of aesthetic preference was more pronounced when the level increased from 55 to 65 dBA; vegetation was found to enhance the aesthetics.

6.3. Relative importance of the operating mechanisms

It has been shown that the 3 identified mechanisms with relation to vegetation can all positively contribute on how environmental noise is perceived. Some comments on their relative importance are made in this section.

The ring road study in Ghent (Van Renterghem and Botteldooren, 2016) is especially interesting as it controls for two aspects namely source visibility and the presence of visible green. At all respondents, at least one driving direction was fully visible from the window at the loud side. The presence of natural sounds, and especially bird sounds, is expected to play a minor role in this setting. Note that the median sound pressure level incident at the outer facade in this study was 73 dBA (L_{den}), so much higher than 55 dBA that already lead to a strong bird avoidance reaction (McClure et al., 2013). Similarly, wind-induced vegetation noise measurements by Fegeant (1999b) show peak levels below 55 dB for a wind speed up to 5 m/s. As a conclusion, the mere presence of visible outdoor green seems sufficient to strongly improve noise perception, regardless of source visibility or of the presence of natural sounds.

The studies by Watts et al. (1999), Zhang et al. (2003) and Sun et al. (2018), focussing on source visibility, can also be analysed in relation to the aesthetic quality of the vegetation. Following Kaplan and Kaplan (1989), the impervious and dense vegetation Sun et al. (2018) used in their window pane videos is far from optimal: such visuals have poor walkability and lack spatial definition; participants do not get the impression that they would be able to function well in such an environment, an assessment that is subconsciously made (Kaplan and Kaplan, 1989). Similarly, the small belts of shrubs and roadside bushes in the work by Watts et al. (1999) are likely to fail in providing fascination, a sense of being-away and extent, so lacking restorative power. Managed, park-like, and semi-open environments, consisting of relatively flat terrain with a sparse number of trees of different species (Misgav, 2000), are much more preferred. The park environment bordered by hedges described in the study of Zhang et al. (2003) could be much more visually immersive than in the study of Watts et al. (1999), although pictures have not been reported. Source visibility aspects can play a role to some extent, but restorative aspects of visually attractive nature seems more prominent and could provide an explanation for the contradicting findings when only considering source visibility.

6.4. Personal characteristics

In the cross-sectional study of Dzhambov and Dimitrova (2015), green space indicators did not have a direct effect on noise annoyance, but indirectly through noise sensitivity (identified by the authors as a mediation effect). The authors of that study mentioned some support from Stansfeld et al. (1993), where it was written that noise sensitivity is not specific to noise but rather a part of general sensitivity to environmental stimuli. However, the latter was contradicted by Schreckenberg et al. (2010) and Zimmer and Ellermeier (1999), concluding that noise sensitivity is a stable personal trait that actually captures attitudes towards a wide range of environmental noises. In addition, twin research showed that there is evidence for an underlying genetic susceptibility to noise sensitivity (Heinonen-Guzejev et al., 2005).

Additional (auditory) deviant detection tests were performed with the same participants as in Sun et al. (2018) in order to assess their audio-visual aptitude (Botteldooren et al., 2017). Based on the scores, an interesting group has been identified namely those that (erroneously) thought they heard a specific source when it was only visible: the vision dominated ones. For these, there was a statistically significant interaction effect with green visuals which seems absent for other groups (Sun et al., 2017). In a related virtual reality experiment with these same participants, the pleasantness was rated during a virtual walk over a bridge crossing a highway (Echevarria-Sanchez et al., 2017b). Auditory dominated persons looked longer and more frequently at the vehicles on the highway than the visually dominated ones (Echevarria-Sanchez et al., 2017a). So, both source visibility and the presence/absence of positive/negative visual environmental features could be linked to personal characteristics.

Hasher and Zacks (1988) reported an age-related decline in divided attention and normal inhibitory processes, suggesting that older adults may be less able than younger ones to suppress a visual distractor. It was found that older people experience greater difficulty in audio-visual speech perception performance in the presence of visual distraction compared to younger listeners (Cohen and Gordon-Salant, 2017). When applied to environmental noise perception, this easier distraction by visuals might actually turn out to be positive.

Connectedness to nature (CN) (Mayer and McPherson-Frantz, 2004) is a personal characteristic shown to be positively correlated with both psychological and social well-being (Howell et al., 2011). The perceived benefits of nature indicator (PBN) (Dzhambov, 2014) could be relevant too here. It can be logically expected that persons scoring high on a CN or PBN scale could benefit more from the positive effect vegetation has on noise perception. In the study by Dzhambov and Dimitrova (2015), higher PBN showed some tendency towards decreasing noise sensitivity.

The research summarized in this section at least suggests that personal characteristics can play a role on how vegetation effects human noise perception. Nevertheless, these findings are far from being conclusive and need further research.

6.5. Equivalent sound pressure level reduction by green visuals

Noise maps, enforced in the European Union since the issuing of the Environmental Noise Directive (END, 2002), have become a major policy instrument for identifying noise polluted zones and action plans. There is a threat that measures that cannot be directly expressed in decibels might not be considered.

Estimating the equivalent noise level reduction could position a perception based measure like visible green relative to more common noise abatement measures (like e.g. a noise wall or silent road surfaces). A specific effect of noise exposure should be kept in mind then like e.g. noise annoyance. This approach has been used before to estimate the effect of the presence of e.g. a quiet side at a dwelling, yielding an equivalent sound pressure level reduction of 5 dBA (de Kluizenaar et al., 2013). Similarly, Lercher (1996) summarized that the aesthetic/natural make up of a site could be as important as 5 dBA. Langdon (1976) found that the perception of the visual appearance of the neighbourhood (like the state of the buildings and streets, the presence of parks, trees and green spaces) is an important predictor of road traffic noise nuisance, and could theoretically amount up to 15 dBA.

In this paragraph, a rough estimate is made of the equivalent noise level reduction for noise annoyance by visible green from home. Using the average dose-effect curves for road traffic as reported by Miedema and Oudshoorn (2001), an equivalent level reduction of 16 dBA L_{den} is obtained in the study by Van Renterghem and Botteldooren (2016). Note that this assessment assumes full linearity of the effect. By using the upper and lower 95% confidence intervals on the average curves, the most conservative approach would still lead to 10 dBA equivalent reduction (for at least moderate annoyance). When comparing the "barrier" visual scenario opposed to the "green" scenario (see Fig. 2a in Leung et al., 2017), such a minimum reduction is close to 11 dBA for high annoyance. The tranquillity study by Pheasant et al. (2008), where a wide range of exposure levels were tested, allows for an estimation of the equivalent level reduction for tranquillity. Following their regression models, the difference between no natural features at all compared to 100% could lead to a shift of 3.6 units on the tranquillity scale, corresponding to an equivalent difference of 33 dBA Leq. Similarly, these values are 2.7 units and 16 dBA, respectively, for Lmax. From these admittedly very rough quantitative estimations, equivalent levels reductions by green visuals could be large, easily exceeding 10 dBA.

This review only considered perception effects with relation to vegetation. Note, however, that physical road traffic noise reduction (that can be measured in decibels, as opposed to the here used equivalent level reduction) is possible as well by designing (even non-deep) woody vegetation belts. The interest reader is referred to Van Renterghem (2014) for a more detailed discussion on this topic. For common sparse or small vegetation belts, the noise perception component is expected to be much stronger than physical sound pressure level reduction.

6.6. Other noise sources than road traffic

Although most research regarding the effect of vegetation on noise perception focuses on road traffic, by far the most prominent source of noise annoyance in the built-up environment, scarce research suggests this idea is also applicable to other environmental noise sources.

The study reported by Lutgen et al. (2017) showed that even a few trees in an urban square in a virtual reality environment are able to improve noise perception during a plane flyover. Vegetation showed to be the dominant factor regarding overall auditory quality and pleasantness of the soundscape, and was even found to be more relevant than a level reduction from 70 to 60 dBA. The noise source during the flyover was clearly visible, stressing the direct effect of the mere presence of green.

Another application is found in Johansson (2005), examining the perception of low frequency noise from ventilation systems inside urban patios. By adding natural sounds, the environment was experienced as significantly more positive than without. The environment was also perceived as significantly more positive when vegetation was present in the visual stimuli.

7. Conclusions

This paper analysed existing research in view of three potentially explaining mechanisms of the positive action of the presence of vegetation on noise perception.

The interaction between source visibility and environmental noise perception is identified as the result of two competing mechanisms namely audio-visual congruency and attention focussing. There is some evidence that hiding the source and thus preventing focussing attention seems optimal when the sound pressure levels are relatively low. At higher levels, audio-visual congruency is necessary and concealing the source should be avoided.

However, the restorative potential of vegetation looks like the dominant mechanism. Visible natural features of good quality can lead to sustained attention restoration and stress relief, counteracting negative outcomes of endured environmental noise exposure. Research on the noise annoyance experienced at home over a long period shows very strong and consistently positive effects when outdoor nature is seen through the dwelling's window, consistent with the micro-restoration hypothesis. There is strong additional support on the importance of natural features in the window view at the working place (higher employee productivity and well-being), in hospital environments (better recovery) and at schools (better grades). Neighbourhood or nearby green, not directly visible from home, shows to be positive as well but has a smaller impact on noise perception. Research shows that with increasing exposure levels, the improvement on the noise perception one can get from visible green is larger.

Natural sounds like bird songs, wind-induced vegetation sounds and water sounds only have limited energetic masking potential for road traffic noise. Informational masking by bird songs, however, seems quite relevant. Natural sounds are generally considered as relaxing on theirselves and support the restorative action of nature by suggesting its nearness.

Based on rough quantitative estimates, the equivalent level reduction of visible green from home with relation to annoyance could reach 10 dBA. Clearly, the green setting should be of sufficient quality and quantity. This positive perception effect could easily outperform physical sound pressure level reductions of common vegetation belts.

There has been a strong focus on road traffic noise, although scarce research suggests that the positive effect is not restricted to this type of source. Personal characteristics might play a role too in the interaction between noise perception and vegetation.

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Appendix A

An overview of the key studies discussed in this work is provided in Table A1. The type of experiment, the noise perception indicator(s) of interest, the number of participants and exposure levels are summarized for each study.

Table A1
Overview of the key studies discussed in this review paper, specifically dealing with the effect of vegetation/natural features on sound perception.

	Type of experiment	Noise perception indicator(s)	Number of respondents	Vegetation/natural features of interest	Exposure level	Full reference
Watts et al. (1999)	Outdoor site visits near roads.	Noisiness during 20-s focused periods.	51	Roadside vegetation belts (real life, outdoor experience).	55–85 dBA Leq.	Watts, G., Chinn L., Godfrey, N., 1999. The effects of vegetation on the perception of traffic noise. Applied Acoustics 56, 39–56.
Sun et al. (2018)	Mock-up living room with video-projection on (virtual) window. Hidden loudspeakers producing transmitted road traffic noise through this window.	Self-reported noise annoyance during 10-min periods (during light activities).	69	Dense and impervious vegetation in the window pane (video, indoor experience).	45–60 dBA Leq.	Sun, K., De Coensel, B., Echevarria-Sanchez, G., Van Renterghem, T., Botteldooren, D., 2018. Effect of interaction between attention focusing capability and visual factors on road traffic noise annoyance. Applied Acoustics 134,16–24.
Zhang et al. (2003)	Passenger-by recruitment at outdoor site with dominant road traffic noise.	Self-reported noise annoyance.	500	Dense hedge in park-environment (real life, outdoor experience).	60–70 dBA.	Zhang, B., Shi, L., Di, G., 2003. The influence of the visibility of the source on the subjective annoyance due to its noise. Applied Acoustics 64, 1205–1215.
Viollon et al. (2002)	Photograph projections on screen and loudspeakers playing a variety of (non-site specific) audio-samples in a dark sound-proof room.	Pleasantness and relaxation potential during 20-s samples.	84	Park and semi-urban environments (photographs).	57–64 dBA Leq.	Viollon, S., Lavandier, C., Drake, C., 2002. Influence of visual setting on sound ratings in an urban environment. Applied Acoustics 63, 493–511.
Pheasant et al. (2008)	Screen projection and headphones in an anechoic room (on-site audio and video recordings).	Tranquillity during (optimized) 32-s audio-visual samples.	44	Natural scenes (including vegetation) (video).	44–78 dBA Leq.	Pheasant, R., Horoshenkov, K., Watts, G., Barrett, B., 2008. The acoustic and visual factors influencing the construction of tranquil space in urban and rural environments: tranquil spaces-quiet places? Journal of the Acoustical Society of America, 123, 1446–1457.
Gidlöf-Gunnarsson and Öhrström (2010)	Postal questionnaire on road traffic noise.	Self-reported noise annoyance at home, perceived residential soundscape, noise-disturbed outdoor activities.	385	Quiet courtyard natural elements (real life, outdoor/indoor experience).	58–68 dBA (Leq, 24 h at most exposed facade).	Gidlöf-Gunnarsson, A., Öhrström, E., 2010. Attractive “quiet” courtyards: A potential modifier of urban residents' responses to road traffic noise? International Journal of Environmental Research and Public Health 7, 3359–3375.
Bodin et al. (2015)	Postal questionnaire on road traffic and railway noise.	Self-reported noise annoyance at home, sleep disturbance, concentration problems.	2612	Yard, water and green space at quiet side of dwelling (real life, outdoor/indoor experience).	from < 40 to > 60 dBA (Leq, 24 h at most exposed facade).	Bodin, T., Björk, J., Ardö, J., Albin, M., 2015. Annoyance, Sleep and Concentration Problems due to Combined Traffic Noise and the Benefit of Quiet Side. International Journal of Environmental Research and Public Health, 12, 1612–1628.
Li et al. (2010)	Interviews at home in two road traffic dominated neighborhoods.	Self-reported noise annoyance at home.	688	Visible greenery (urban parks and wetlands) as seen from high-rise buildings (real life, indoor experience).	60–70 dBA (CRTN calculated).	Li, H., Chau, C., Tang, S., 2010. Can surrounding greenery reduce noise annoyance at home? Science of the Total Environment 408, 4376–4384.
Van Renterghem and Botteldooren (2016)	Interviews at home along busy inner city ring road.	Self-reported noise annoyance at home.	105	Greenery as seen from the living room window (park edges, lawns, street trees) in European style closed-row urban setting (real life, indoor experience).	65–80 dBA Lden at most exposed facade (mean 73 dBA Lden).	Van Renterghem, T., Botteldooren, D., 2016. View on outdoor vegetation reduces noise annoyance for dwellers near busy roads. Landscape and Urban Planning 148, 203–215.
Leung et al. (2017)	Interviews in the public space near dwellings at 5 neighborhoods with road traffic as major noise source.	Self-reported noise annoyance at home.	2033	Visible greenery and water space as seen from high-rise buildings (real life, indoor experience).	46–75 dBA (mean 64 dBA), L10,1 h.	Leung, T., Xu, J., Chau, C., Tang, S., Pun-Cheng, L., 2017. The effects of neighborhood views containing multiple environmental features on road traffic noise perception at dwellings. The Journal of the Acoustical Society of America 141, 2399–2407.
Yang et al. (2011)			40	Park environment (virtual reality video).	63–69 dBA Leq.	

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Table A1 (*continued*)

	Type of experiment	Noise perception indicator(s)	Number of respondents	Vegetation/natural features of interest	Exposure level	Full reference
	Video recordings projected on video glasses, loudspeakers with in-situ road traffic noise.	Emotional tests using electroencephalograms (EEG).				Yang, F., Bao, Z., Zhu, Z., 2011. An assessment of psychological noise reduction by landscape plants. International Journal of Environmental Research and Public Health 8, 1032–1048.
Yang and Kang (2015)	Interviews at two urban squares.	Preferred types of urban sounds.	1009	Bird songs, water sounds, insect sounds.	60–72 dBA Leq.	Yang, W., Kang, J., 2005. Soundscapes and sound preferences in urban squares. Journal of Urban Design 10, 69–88.
Hong and Jeon (2013)	Projected photographs in combination with in-situ road traffic noise and added water/bird sounds.	Preference rating and soundscape/ streetscape components like pleasantness, variability, loudness, congruity and spatial impression during 6-s samples.	20	Vegetation (trees, hedges) and water features added on urban photograph by image processing.	55–70 dBA Leq.	Hong, J., Jeon, J., 2013. Designing sound and visual components for enhancement of urban soundscapes. Journal of the Acoustical Society of America 134, 2026–2036.
Krzywicka and Byrka (2017)	Listening through headphones to a variety of natural and urban sounds, imagined sound walks while playing best rated natural sounds (loudspeaker setup).	Potential to induce positive feelings after 2-min samples, perceived restorative quality of sounds during 30-s samples, etc.	88/120	Natural sounds only, no visual nature.	Adjustable by participants.	Krzywicka, P., Byrka, K., 2017. Restorative Qualities of and Preference for Natural and Urban Soundscapes. Frontiers in Psychology 8:1705.
Hao et al. (2015)	Noise mapping and loudness modelling.	(Simulated) loudness.	No persons involved.	Songbirds in urban trees (using a typical sound level spectrum).	56–73 dB.	Hao, Y., Kang, J., Krijnders, J., 2015. Integrated effects of urban morphology on birdsong loudness and visibility of green areas. Landscape and Urban Planning 137, 149–162.
Hedblom et al. (2017)	Postal survey of dwellers living adjacent to urban green spaces.	Desirability/calmness of natural sounds.	1326	Songbirds in urban green spaces experienced in their neighbourhood.	Unknown.	Hedblom, M., Knez, I., Ode Sang, Å., Gunnarsson, B., 2017. Evaluation of natural sounds in urban greenery: potential impact for urban nature preservation. Royal Society Open Science 4: 170037.
Ratcliffe et al. (2013)	In-depth interviews.	Perceived attention restoration and stress recovery by bird sounds.	20	Past experience with relation to bird songs.	Not relevant.	Ratcliffe, E., Gatersleben, B., Sowden, P., 2013. Bird sounds and their contributions to perceived attention restoration and stress recovery. Journal of Environmental Psychology, 36, 221–228.
Alvarsson et al. (2010)	Stress recovery experiment after demanding mental task.	Skin conductance level and high frequency heart rate variability after 4-min exposure.	40	Natural sounds (water sounds and tweeting birds), no visuals.	50 dBA Leq.	Alvarsson, J., Wiens, S., Nilsson, M., 2010. Stress Recovery during Exposure to Nature Sound and Environmental Noise. International Journal of Environmental Research and Public Health 7, 1036–1046.
Oldoni et al. (2013)	Auditory attention model of environmental sounds.	Simulated audibility/partial loudness of bird songs, simulated auditory attention.	No persons involved.	Bird songs (bird chirps and bird chorus).	68 dBA Leq urban sound with various signal-to-noise ratios for bird sounds.	Oldoni, D., De Coensel, B., Boes, M., Rademaker, M., De Baets, B., Van Renterghem, T., Botteldooren, D., 2013. A computational model of auditory attention for use in soundscape research. Journal of the Acoustical Society of America 134, 852–861.
Bolin et al. (2010)	Masking experiment with relation to wind turbine noise in an anechoic room (using headphones).	Masking threshold and (partial) loudness (several seconds of exposure).	30	Wind-induced vegetation noise, no visuals.	Wide range of signal-to-noise ratios, 35–55 dBA Leq, 1 s.	Bolin, K., Nilsson, M., Khan, S., 2010. The potential of natural sounds to mask wind turbine noise. Acta Acustica United Acustica 96, 131–137.
Galbrun and Ali (2013)	Listening test of combination of water sounds and road traffic noise in an anechoic room (using headphones).	Peacefulness and relaxation potential during 7-s samples.	34	Variety of water sounds (waterfalls, fountains, jets, cascades, streams), no visuals.	55 dBA Leq road traffic noise, with various signal-to-noise ratios of water sounds.	Galbrun, L., Ali, T., 2013. Acoustical and perceptual assessment of water sounds and their use over road traffic noise. Journal of the Acoustical Society of America 133, 227–237.

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Table A1 (*continued*)

	Type of experiment	Noise perception indicator(s)	Number of respondents	Vegetation/natural features of interest	Exposure level	Full reference
Jeon et al. (2010)	Listening test of a combination of unwanted sounds (road traffic noise and various types of construction noise) and natural sounds (using headphones in sound proof chamber).	Self-reported noise annoyance, acoustic comfort, loudness, preference.	12	Variety of water sounds (waterfall, rain, stream, waves on lake), birds, insects, wind noise. Urban photograph as visual.	40–90 dBA Leq.	Jeon, J., Lee, P., You, J., Kang, J., 2010. Perceptual assessment of quality of urban soundscapes with combined noise sources and water sounds. Journal of the Acoustical Society of America 127, 1357–1366.
You et al. (2010)	Listening test of a combination of road traffic noise and water sounds (using headphones in sound proof chamber).	Preference, pleasantness, acoustic comfort.	20	Variety of water sounds (fountains, streams, water sculptures, waterfalls) measured in-situ at urban squares.	55 dBA and 75 dBA.	You, J., Lee, P., Jeon, J., 2010. Evaluating water sounds to improve the soundscape of urban areas affected by traffic noise. Noise Control Engineering Journal 58, 477–483.
Nilsson et al. (2010)	Auditory masking experiment in a semi-sound proof room through headphones.	Partial loudness during 5-s intervals.	17	Large jet fountain in an urban park.	59–73 dBA Leq, 5 s.	Nilsson, M., Alvarsson, J., Radsten-Ekman, M., Bolin, K., 2010. Auditory masking of wanted and unwanted sounds in a city park. Noise Control Engineering Journal 58, 524–531.

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