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Combined acoustical and visual performance of noise barriers in mitigating the environmental impact of motorways

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Abstract

This study investigated the overall performance of noise barriers in mitigating environmental impact of motorways, taking into consideration their effects on reducing noise and visual intrusions of moving traffic, but also potentially inducing visual impact themselves. A laboratory experiment was carried out, using computer-visualised video scenes and motorway traffic noise recordings to present experimental scenarios covering two traffic levels, two distances of receiver to road, two types of background landscape, and five barrier conditions including motorway only, motorway with tree belt, motorways with 3 m timber barrier, 5 m timber barrier, and 5 m transparent barrier. Responses from 30 participants of university students were gathered and perceived barrier performance analysed. The results show that noise barriers were always beneficial in mitigating environmental impact of motorways, or made no significant changes in environmental quality when the impact of motorways was low. Overall, barriers only offered similar mitigation effect as compared to tree belt, but showed some potential to be more advantageous when traffic level went high. 5 m timber barrier tended to perform better than the 3 m one at the distance of 300 m but not at 100 m possibly due to its negative visual effect when getting closer. The transparent barrier did not perform much differently from the timber barriers but tended to be the least effective in most scenarios. Some low positive correlations were found between aesthetic preference for barriers and environmental impact reduction by the barriers.

Keywords: Traffic noise; visual impact; noise barrier; audio-visual performance; multisensory perception

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1. Introduction

The growing concern about noise pollution has increased the use of noise barriers along major transport infrastructures (Kotzen & English, 2009). Noise barriers come in various sizes, forms, placements and materials and can reduce noise up to about 15 dBA realistically in practice (Kotzen & English, 2009). Evaluation of noise barriers requires however more than the measurement of noise reduction. Studies on perceived effectiveness of noise barrier have shown influences of factors other than acoustical performance, e.g., before-barrier sound levels (May & Osman 1980), engagement in the barrier design (Hall 1980, Joynt 2005), social and economic effects, e.g., changes in property value and risk of crime (Perfater, 1979).

Among the influential factors, visual factor is a major one and many studies have investigated the effect of it. Aylor and Marks (1976) studied the perceived loudness of noise transmitted through barriers of different solidity in “sight + sound” and “sound only” conditions. The results showed lower perceived loudness when the sight of the noise source was partially obscured; but higher perceived loudness when the sight of noise source was completely obscured. Similar results were found in Watts et al. (1999) where the effect of vegetation on traffic noise perception was investigated both on site and in laboratory. It was shown that perceived noisiness was higher where the level on visual screening of the sound source by vegetation was higher. In their laboratory experiment, a willow barrier and a metal barrier of the same dimension were also included in the assessment. While participants rated the willow barrier more attractive than the metal one, similar perceived noisiness behind the two barriers was reported. Joynt & Kang (2010) conducted a more dedicated and detailed study on the effect of barrier aesthetics. The study compared perceived effectiveness of four motorway noise barriers and a deciduous hedgerow in a laboratory experiment. The results showed a strong negative correlation between aesthetic preference and the perceived noise attenuation of the barriers. The study also investigated the effect of preconception of barrier effectiveness on the perceived noise attenuation and found positive correlation between them. Lower perceived loudness behind the opaque barriers was found in this study which was contradictory to that in Watts et al. (1999) and Aylor & Marks (1976). Maffei et al. (2013) studied the effect of barrier aesthetics and noise source visibility through barriers on the perceived loudness and annoyance of railway noise. The results was more in line with Watts et al. (1999) and Aylor & Marks (1976), that perceived loudness was lower for transparent barriers than for opaque barriers, and remained largely the same for barriers of different aesthetics. Noise annoyance was perceived lower for transparent barriers as well, and for barriers with higher aesthetics. The effect of visual characteristics increased as noise level increased.

The above studies show that perceived effectiveness of noise barriers are influenced by noise source visibility and barriers aesthetics in complex ways, requiring the use of aural-visual interaction approaches for the assessment of barriers. While some studies investigated either the effect of visual stimuli on sound environment perception (e.g., Anderson et al., 1984; Liu et al., 2014; Mulligan et al., 1987; Ren and Kang, 2015; Viollon et al., 2002), or audio stimuli on visual environment perception (e.g., Anderson et al. 1983; Benfield et al., 2010; Hetherington et al., 1993), many have focused on their interactive effects on the perception of the overall quality of the environment (e.g., Carles et al, 1999; Hong & Jeon, 2013; Pheasant et al., 2008). Nilsson et al. (2012) argued that assessing the overall environmental quality is easier and more natural than assessing environmental qualities of each individual sensorial modality, which is particularly applicable for the case of noise barriers, as design and installation of noise barriers is also a landscape issue: while they are aimed to be acoustically beneficial, they are often visually intrusive and can restrict sight of desired views (Arenas, 2008, Bendtsen, 1994, Kotzen & English, 2009).

Following this argument, Hong & Jeon (2014) studied the overall preference for noise barriers considering both audio and visual performances. Their results show that vegetated barrier was the most preferable one, followed by concrete and wood barriers, translucent acrylic and aluminium barriers were the least preferred, despite the lower perceived loudness found for transparent and nonsolid barriers in Aylor & Marks (1976), Maffei et al. (2013) and Watts et al. (1999). Preconception of barriers' noise reduction effectiveness was the most affecting factor in determining the overall preference for the barriers when the noise level was relatively low (55 dBA), while aesthetic preference for barriers came to be the most determinant one when noise level was relatively high (65 dBA).

The results of Hong & Jeon (2014) are informative and indicate potential improvement that could be made for the evaluation of noise barriers by evaluating their overall environmental performance. However, one limitation of Hong & Jeon (2014) is the use of static images to present noise barriers for road traffic in their experiment. It failed to present moving traffic which should be visible in some barrier scenarios, while moving traffic has been shown to be influential on perceptions of both sound (Fastl, 2004) and visual (Gigg, 1980; Huddart, 1978) environmental qualities. Moreover, there is a lack of investigations on the effects of background landscape and receiver distance to road on the perceived barrier performance in previous multisensory-based noise barriers studies. Background landscape is not only one of the decisive factors in determining the visual effect that a certain development can have on human viewers (Landscape Institute and Institute of Environmental Management and Assessment, 2013), it is also influential on noise perception (Mulligan et al., 1987; Viollon et al., 2002) and can thus affect the perceived acoustic performance of the barriers. Receiver distance to road is also not only critical for visual impact assessment (Landscape Institute and Institute of Environmental Management and Assessment, 2013), but for the measured net benefit that barriers can have on certain receivers as well (Highways Agency, 2001a). Herman et al. (1997) showed that perceived effectiveness of barriers was also distance-dependant.

Therefore, the aim of this study is to investigate the overall performance of noise barriers in mitigating environmental impact of motorways, taking into consideration their effects on reducing noise and visual intrusions of moving traffic, but also potentially inducing visual impact themselves. Specifically, the study is to answer the following questions: (1) Are noise barriers always beneficial in mitigating environmental impact of motorways and how beneficial are they given different traffic levels, receiver distances to road and background landscapes? (2) How do barriers of different acoustical and visual characteristics differ in their performance in the varied scenarios? (3) Do aesthetic preference for barriers and preconception of their noise reduction effectiveness influence the perceived overall performance of them? A laboratory experiment was carried out to obtain subjective responses to computer-visualised video scenes representing different experimental scenarios, including scenes without motorways, scenes with motorways, and scenes with motorways and barriers varying in size and transparency. Performances of barriers were compared in terms of reductions in perceived environmental impact of motorways in different scenarios.

2. Methods

2.1. Design of the experimental scenarios

Three barrier scenarios were designed to represent barriers varying in transparency and size: 3-m-tall timber barrier, 5-m-tall timber barrier, 5-m-tall transparent barrier. Timber material was preferred over metal, concrete, brick etc. for the opaque barrier because timber barriers are the most commonly used type of barriers for mitigation of road traffic noise in the UK (Kotzen & English, 2009). The height of timber barriers in the UK rarely exceeds 3 m (Kotzen & English, 2009; Morgan, 2010) and there was a general restriction on barrier height of 3m in the UK to avoid visual intrusion (Highway Agency, 2001b). However, timber barriers are recently increasing in height and those in the Europe can reach 4-5 m tall (Kotzen & English, 2009; Morgan, 2010). So the heights of 3 m and 5 m were used for the two timber barrier scenarios, which are realistic in scale and typical for the visual concerns while offer adequate difference in noise reduction. Transparent barriers can be made from several materials and there is less restriction in their heights. The height of 5 m, the same as the taller timber barrier, was used for the transparent barrier to control noise reduction. Two scenarios without barriers, one with the motorway only and one with a tree belt partially screening the motorway, were also designed to offer comparisons, as well as a baseline scenario without motorways.

Two distances of receiver to the motorway, 100 m and 300 m, were chosen for this study. 100 m was chosen for the shorter distance scenario instead of a very close distance (e.g. 2 m in Hong &Jeon (2014)), since relatively far receiver positions are more common in cases of motorways and 100 m was thought to be more typical for the majority of the affected population, and noise reduction by barriers can still be significant at 100 m even when the ground is absorbing (Highways Agency, 2001a). 300 m was chosen for the longer distance scenario because this is around the threshold beyond which barriers may only offer negligible noise reduction (Highways Agency, 2001a) while people can still be adversely affected by noise of high volume traffic (Kotzen & English, 2009) and be visually affected by the barrier (Highways Agency, 1993; Jiang et al., 2015). People in the 300 m distance scenarios are not likely to be the group that the barriers are aimed to benefit, the idea is to see what potential environmental effects, positive or negative, that barriers can still have on this group.

Two traffic levels, 2046 vehicle/hour with 10% heavy good vehicle (HGV), and 10928 vehicle/hour with 20% HGV, were designed for this study. The values of these chosen traffic flows and compositions were determined based on the annual traffic count of UK motorways (Department for Transport, 2014; Highway Agency, 2004), aiming to make adequate difference between the two levels while keep them representative and reasonable for a motorway like M1. Speed of 110km/h was assigned to cars and 90km/h assigned to HGVs according to the UK motorway speed limits (GOV.UK, 2014).

Two types of background landscape, natural and residential landscapes, which are typical along the motorway corridors in the UK, were conceived for this study. A summary of the experimental scenarios can be found in Figure 1.

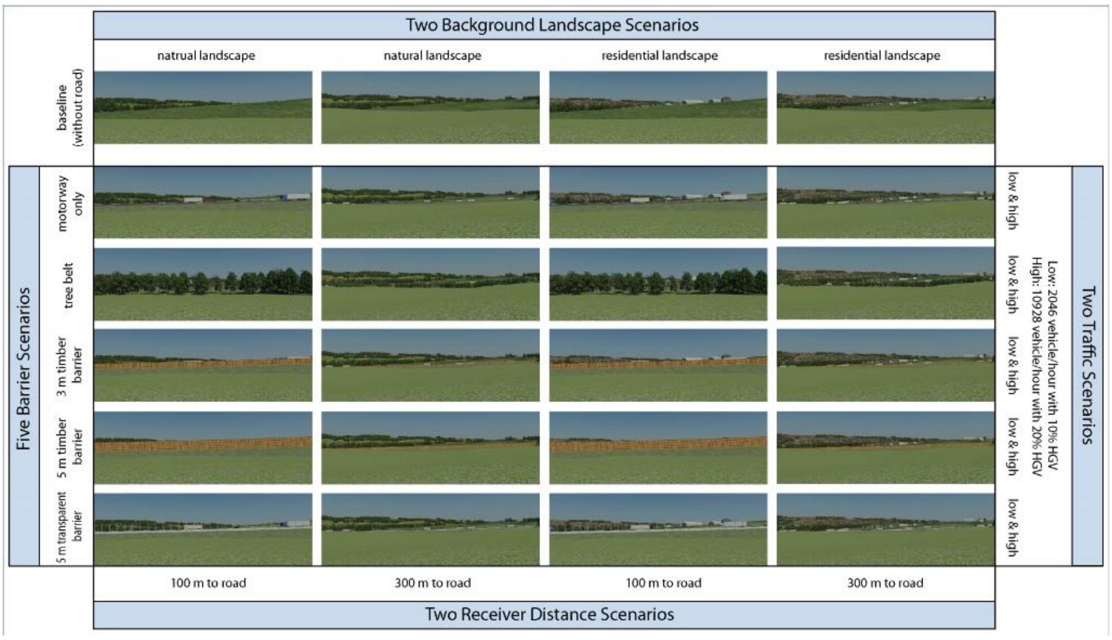

Figure 1. Designed experimental scenarios.

2.2. Preparation of visual stimuli

A site along a segment of the UK M1 motorway between Junction 34 and 35, covering an area of 2500 m × 2500 m, was chosen as the base site for computer visualisation. The dimensions of cross-section components for rural motorway mainline provided by Highways Agency (Highways Agency, 2005) was used to model the motorway which was dual-three lane. The motorway and its surrounding landscape, including trees and buildings, were modelled in Autodesk 3ds Max Design, with geo-data of the site obtained from Ordnance Survey.

The designed natural and residential landscape scenarios were created based on the 3D model of the existing landscape by changing the amount of buildings and trees. Barriers for the three barrier scenarios were modelled according to parameters and photos demonstrated in Kotzen & English (2009) and Morgan (2010), and then added alongside the motorway for each scenario. Animations of moving traffic were made for the two traffic levels, with 10 cars and 1 HGV for the low level and 49 cars and 12 HGVs for the high level in 20 seconds which was the length of each video scene that would be rendered. The motorway was removed in baseline scenarios. Two viewpoints, 100 m and 300 m away respectively from the near edge of the motorway, were assigned in the models for the two distance scenarios. Cameras to capture views from the two viewpoints were set 1.6 m above the ground facing perpendicular to the motorway.

The captured views were rendered into video scenes with the animations of moving traffic. The resolution of the rendering was 1800 × 600 pixels at a frame rate of 30 fps. Each video scene was 20 seconds long. The scenes of baseline scenarios, where there was no moving traffic, were still images and each lasted 10 seconds. In total, 40 video scenes and 4 image scenes were produced, and were merged in a random order to create a single long video, with the scene number (Scene 1 to Scene 44) appearing for 3 seconds before each scene and a 3-second blank interval after each scene. Another long video was made with scenes in reversed order. The two videos would be equally but randomly assigned to the participant sessions to eliminate the possible effect of scene order.

2.3. Preparation of audio stimuli

Audio recordings of the M1 traffic noise was made on site using a digital recorder Sound Devices 722 and a pair of DPA 4060 Miniature Omnidirectional Microphones, worn by an operator facing perpendicularly to the road. The traffic flow was generally consistent during the recordings. Due to the inaccessibility of the recording locations of 100 m and 300 m, 230 m and 350 m recording locations were used, and the sound files were then adjusted to reflect the level at 100 m and 300 m respectively, for reproduction of audio stimuli to be used in this study.

A 20-second sample was extracted from each of the two full audio recordings for audio reproduction. The recording sample was calibrated with the signal of a 01dB Cal01 Calibrator (94 dB/1 kHz) using a Neumann KU 100 dummy head and the playback system (see Section 2.4) that would be used for the experiment. The obtained sound equivalent level of the 20-second sample from 230 m was 70.4 dBA, and that from 350 m was 63.1 dBA.

The required sound pressure level at receiver position in each scenario was calculated using the noise prediction software CadnaA. For the calculation, the absorption coefficient of the ground, which was grassland in this study, was set as 0.5. The UK CRTN model was used to calculate the noise levels with and without barriers (Department of Transport, 1988). Tree belt was treated as without barrier. The obtained $LA_{10,18h}$ levels were further converted to LAeq,18h levels (Abbott & Nelson, 2002). The calculated levels for each scenario are shown in Table 1.

Table 1. Sound pressure level at receiver position for each scenario.

Scenario			Sound pressure level (dBA)				
			Without barrier	**Tree belt**	**3 m timber barrier**	**5 m timber barrier**	**5 m transparent barrier**
High traffic level	**100 m distance**	**Natural landscape**	73.9	73.9	64.4	62.1	62.1
		Residential landscape	73.9	73.9	64.4	62.1	62.1
	300 m distance	**Natural landscape**	66.9	66.9	62.1	61.3	61.3
		Residential landscape	66.9	66.9	62.1	61.3	61.3
Low traffic level	**100 m distance**	**Natural landscape**	65.4	65.4	56.0	53.7	53.7
		Residential landscape	65.4	65.4	56.0	53.7	53.7
	300 m distance	**Natural landscape**	58.4	58.4	53.6	52.8	52.8
		Residential landscape	58.4	58.4	53.6	52.8	52.8

To produce audio files for received traffic noise without barrier, the original recordings were edited in Adobe Audition CS6, either by increasing or by decreasing the overall levels within an appropriate range. The 230 m recording (70.4 dBA) was used to produce audio files for high traffic level at 100 m (73.9 dBA) and 300 m (66.9 dBA); and the 350 m recording (63.1 dBA) was used to produce audio files for low traffic level at 100 m (65.4 dBA) and 300 m (58.4 dBA). To produce audio files for received traffic noise with barrier, the levels of the audio files for without barrier were further edited in one-octave band. Since CRTN does not provide spectrum information, Maekawa's chart (Maekawa, 1968) was used as a guidance to help decide noise reduction on each octave band. The produced audio files were again calibrated to check if their playbacks meet the required levels.

For baseline scenarios without motorway, bird song was used as audio stimulus, since it was the main background sound at the recording site. Audio recording of bird sound was obtained in a quiet suburban park and an 8-second sample was extracted for use. The played-back level of the extracted sample was 47.8 dBA.

The audio files were then added to the soundtracks of the videos

2.4. The experiment and procedure

Thirty participants of university students (15 male and 15 female), aged 18-27 (Avg. = 21.1, S.D. = 2.1), with normal hearing and normal or adjusted to normal vision, were recruited via email invitation within the university. Each participant session took about 25 minutes and the participant received a small amount of cash as compensation for his/her time.

The experiment was carried out in a 3.5m × 3.5m × 2.3m anechoic chamber. The videos were played by an ASUS X550C laptop and projected via a Hitachi ED-X33 LCD projector onto a 203 cm × 152 cm screen 2.2 m away from where the participants were seated. Sound was presented to participants via a pair of Beyerdynamic DT 770 Pro headphones.

During the experiment, participants were asked to rate the overall pleasantness of each scene using visual analogue scale, that is, by marking a "×" on a bar which was 100 mm long on the printed questionnaire and had only "low pleasantness" and "high pleasantness" labelled at the two ends. Before start, participants were told that the term overall pleasantness in this study concerned mainly visual pleasantness and sound pleasantness, but the purpose of this study was not mentioned. When the video of the 44 scenes ended, participants were shown on the screen an image of the three barriers used in this study (Figure 2), and asked to rate the aesthetic quality and noise reduction effectiveness of each barrier, based on their own preference or knowledge, regardless of what they had seen or heard in the earlier video session.

2.5. Analysis of the results

Overall pleasantness of each scene was measured on questionnaires as the length from the low-pleasantness end of the visual analogue scale bar to the marked "×" on the bar in millimetre. So possible overall pleasantness scores would range from 0 to 100. The perceived environmental impact of motorway in each scene with motorway (including motorway only, motorway with barrier, and motorway with tree belt) was calculated by subtracting the overall pleasantness score of the scene from overall pleasantness score of the corresponding baseline scene without motorway. Possible environmental impact scores would thus range from -100 to 100, where a negative value means the motorway enhances the overall pleasantness whereas a positive value means the motorway decreases the overall pleasantness, the larger the absolute value the higher the degree of impact. The mitigation effect of each barrier or the tree belt was measured as reduction in environmental impact as compared to the corresponding scene with motorway only.

The five barrier conditions: motorway only, tree belt, 3 m timber barrier, 5 m timber barrier and 5 m transparent barrier, were treated as the five levels of the barrier condition variable. Within-subject ANOVAs were run to analyse the effects of barrier condition, traffic level, distance and background landscape on the perceived environmental impact of motorways, and to compare the mitigation effect of barriers in each traffic, distance and landscape scenarios. Correlation analysis was undertaken to test the relationship between aesthetic preference for barriers, preconception of effectiveness of the barriers, and perceived environmental impact reduction by the barriers. All statistical analysis was carried out using IBM SPSS Statistics 21.

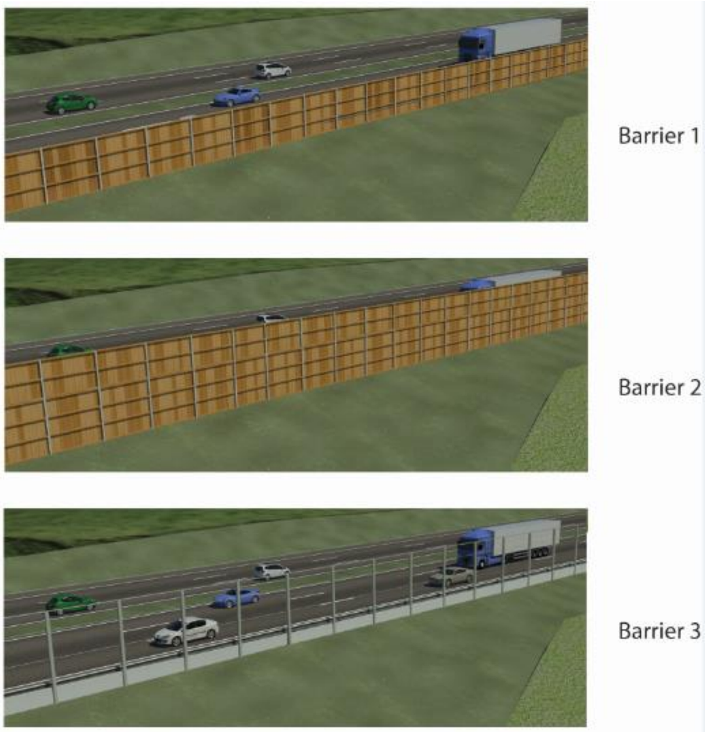

Figure 2. Image of the three barriers for aesthetic and effectiveness ratings.

3. Results

3.1. An overall analysis of the results

A 5 × 2 × 2 × 2 within subject ANOVA was carried out for an overall analysis of the effects of barrier condition, traffic level, distance and background landscape on the perceived environmental impact of motorways. The result shows that all the four factors had significant effect on the perceived environmental impact (Greenhouse-Geisser correction was applied where assumption of sphericity was violated), barrier condition: F-ratio (F) = 27.445, degrees of freedom (df) = 2.997, 86.922, *p*-value (*p*) $< .001$, partial eta squared (η^2_p) = .486; traffic level: F = 141.426, df = 1, 29, $p < .001$, $\eta^2_p = .830$; distance: F = 57.211, df = 1, 29, $p < .001$, $\eta^2_p = .664$; background landscape: F = 17.196, df = 1, 29, $p < .001$, $\eta^2_p = .372$. The values of partial eta squared show that barrier condition had an medium effect, which is smaller than that of traffic level and distance but larger than that of background landscape, on the perceived environmental impact. Within the effect of barrier condition, marginal mean comparison shows that, while environmental impact was significantly higher without barrier than in any other barrier conditions ($p < .001$), no significant difference was found between any of the other barrier conditions, which indicates that, generally the three barriers and the tree belt could all reduce the environmental impact of motorways, however, despite of their differences in visual appearance and noise reduction ability, their general performance over the eight experimental scenarios (two travel levels × two distances × two background landscapes) was largely the same with each other.

Significant interaction effect related to barrier condition was found between traffic level and barrier condition: F = 6.102, df = 4, 116, $p < .001$, $\eta^2_p = .174$; between distance and barrier condition: F = 9.807, df = 2.958, 85.789, $p < .001$, $\eta^2_p = .253$; among traffic level, distance and barrier condition: F = 3.248, df = 4, 116, $p = .014$, $\eta^2_p = .101$; and among background landscape, distance and barrier condition: F = 2.939, df = 4, 116, $p = .023$, $\eta^2_p = .092$. It indicates that barrier performance might change with specific scenarios especially distance and traffic scenarios.

To analyse the effect of barrier condition in each individual experimental scenario, eight one-way within-subject ANOVAs were undertaken, using barrier condition as independent variable and environmental impact score as dependent variable. Table 2 lists the results. It shows that barrier condition had significant effect in all scenarios except the two with low traffic level at 300 m, which means barriers or tree belt made no significant aggravation or mitigation of environmental impact in these two scenarios. The values of partial eta squared indicate that the effect of barrier condition was larger with high traffic level than with low traffic level, at 100 m than at 300 m, and in residential landscape than in natural landscape.

Figure 3, together with Table 3, compares the mean environmental impact in the five barrier conditions for each experimental scenario. The figure and table show that environmental impact varied to some extents among the barrier conditions as well as across the eight scenarios. Detailed analysis of the comparison is presented in Section 3.2 and 3.3.

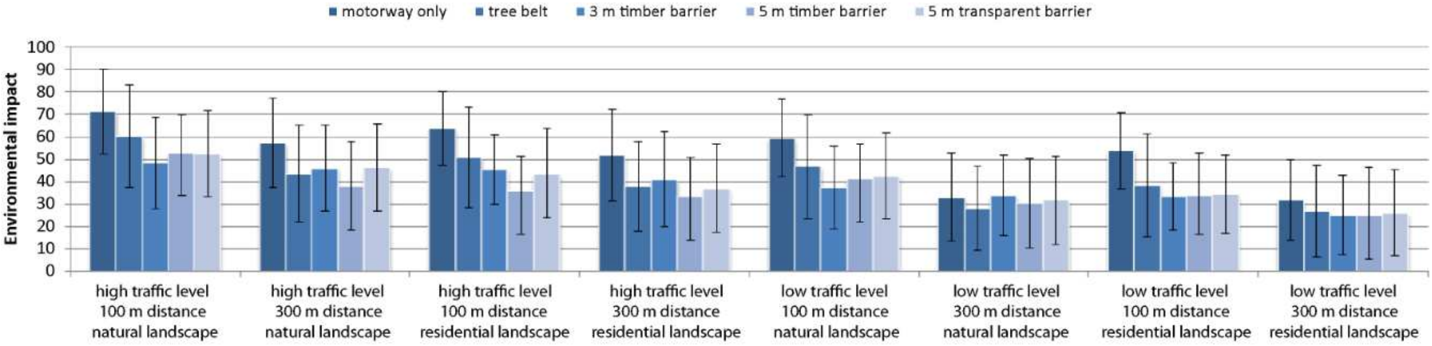

Figure 3. Mean environmental impact in the five barrier conditions for each of the eight experimental scenarios. Error bar represents one standard deviation.

Table 3. Pairwise marginal mean comparisons of environmental impact scores in different barrier conditions.

Barrier condition (a)	Barrier condition (b)	Mean difference (a-b) (reduction in environmental impact score)							
		High traffic level				Low traffic level			
		100 m distance		300 m distance		100 m distance		300 m distance	
		Natural	Residential	Natural	Residential	Natural	Residential	Natural	Residential
Motorway only	Tree belt	11.200*	18.333*	13.767*	13.733*	22.100*	20.533*	5.033	6.700
	3 m timber	23.200*	27.700*	11.300*	10.733*	18.100*	19.833*	-.667	6.933
	5 m timber	18.400*	20.267*	19.500*	18.067*	16.667*	19.467*	2.600	5.733
	5 m transparent	18.933*	12.833*	11.067*	14.733*	12.567*	15.533*	1.367	5.000
Tree belt	3 m timber	12.000*	9.367*	-2.467	-3.000	-4.000	-.700	-5.700	.233
	5 m timber	7.200	1.933	5.733	4.333	-5.433	-1.067	-2.433	-.967
	5 m transparent	7.733	-5.500	-2.700	1.000	-9.533	-5.000	-3.667	-1.700
3 m timber	5 m timber	-4.800	-7.433	8.200*	7.333	-1.433	-.367	3.267	-1.200
	5 m transparent	-4.267	-14.867*	-.233	4.000	-5.533	-4.300	2.033	-1.933
5 m timber	5 m transparent	.533	-7.433	-8.433	-3.333	-4.100	-3.933	-1.233	-.733

* The mean difference is significant at the .05 level, Bonferroni correction applied.

3.2. Comparison of barriers with motorway only and tree belt.

It can be seen in Figure 3 that environmental impact in the three barrier conditions was consistently lower than that in the motorway-only condition. Pairwise comparisons in Table 3 show that the reductions in environmental impact by barriers were all significant in scenarios where the effect of barrier condition was significant. It suggests that the use of barriers, when effective, was always beneficial in mitigating environmental impact of motorways.

The mitigation effect of 3 m timber barrier was highest in the high traffic × 100 m × residential landscape scenario, followed by in the high traffic × 100 m × natural landscape scenario, with a reduction in mean environmental impact score of 27.2 and 23.2 respectively. Generally, the mitigation effect was larger with high traffic level than with low traffic level, and larger at 100 m than at 300 m. The mitigation effect of 5 m timber barrier was relatively constant across all the scenarios in which it was significant, with reductions in mean environmental impact score ranging from 16.7 to 20.3. The mitigation effect of 5 m transparent barrier was highest in the high traffic × 100 m × natural landscape scenario, with a reduction in mean environmental impact score of 18.9. The mitigation effect varied to some extent across the scenarios in which it was significant, but did not show clear tendency in relation to scenario types.

Compared to tree belt, the three barriers did not show many significant differences. Only 3 m timber barrier, in the high traffic × 100 m scenarios where the potential impact of motorways was highest, reduced environmental impact significantly more than the tree belt did. No other significant difference was found between 3 m timber barrier and tree belt, 5 m timber barrier and tree belt, or 5 m transparent barrier and tree belt. However, there did seem to be some tendency that 5 m timber barrier reduced environmental impact slightly more than tree belt did when traffic level was high and slightly less than tree belt did when traffic level was low.

3.3. Comparison between the three barriers

Comparing 3 m timber barrier with 5 m timber barrier in Table 3, significant difference was only found in high traffic × 300 m × natural landscape scenario, where 5 m timber barrier reduced environmental impact 8.2 more than 3 m timber barrier did. However, although insignificant, the mean differences suggest some tendency that, when traffic level was high, 5 m timber barrier was more effective than its 3 m counterpart at 300 m and less effective than its 3 m counterpart at 100 m; when traffic level was low, the difference between their performances became less clear.

Comparing 3 m timber barrier with 5 m transparent barrier, significant difference was only found in the high traffic × 100 m × residential landscape scenario, where 3 m timber barrier reduced environmental impact 14.9 more than 5 m transparent barrier did. However, the mostly negative mean differences, despite their insignificance, imply that 3 m timber barrier seemed likely to be more effective than 5 m transparent barrier in most scenarios.

No significant difference was found between 5 m timber barrier and 5 m transparent barrier in any scenarios. But again, the mostly negative mean differences imply that 5 m timber barrier seemed likely to be more effective than 5 m transparent barrier in most scenarios.

3.4 Aesthetic preference and preconception of noise reduction effectiveness

Figure 4 shows participants' aesthetic preference for the three barriers used in this study and their preconception of the barriers' noise reduction effectiveness. On average, participants did not have strong aesthetic preference for any of the barriers over the other two. One-way ANOVA shows no significant difference among the three barriers: F = 1.467, df = 1.515, 43.946, p = .241, η^2_p = .048. The error bars show some variation among individual participants though. As for preconception of noise reduction effectiveness, significant difference was found among the three barriers: F = 28.889, df = 1.337, 38.772, p < .001, η^2_p = .499. Participants generally considered 3 m timber barrier less effective than 5 m timber barrier and 5 m transparent barrier (p < .001 in both cases); and considered 5 m timber barrier and 5 m transparent barrier equally effective (p = 1), yet again the error bars indicate some variation among individual participants . No significant correlation was found between aesthetic preference and preconception of effectiveness (p = .064).

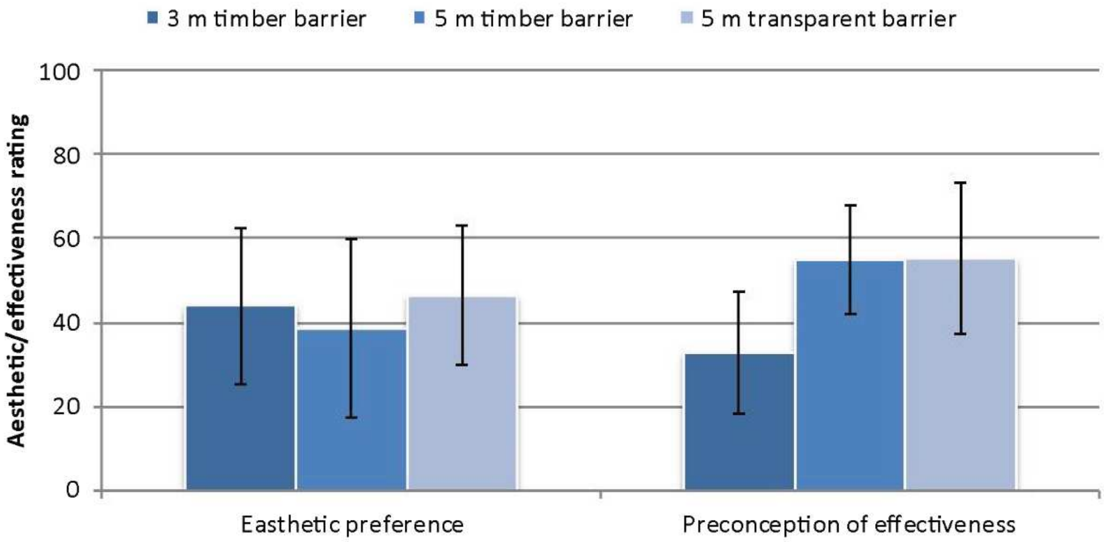

Figure 4. Mean scores of aesthetic preference for barriers and preconception of barriers' noise reduction effectiveness. Error bar represents one standard deviation.

Correlations between aesthetic preference for barriers and environmental impact reduction, and between preconception of their noise reduction effectiveness and environmental impact reduction, were carried out for each of the eight experimental scenarios, to analyse if they have any connections with the perceived environmental performance of barriers at individual participant level. Table 4 shows the results. Significant and positive correlation at low level was found between aesthetic preference and environmental impact reduction in all the residential scenarios, which implies that in residential landscape, barriers regarded as more aesthetically pleasing had some slight advantage in achieving better environmental performance. No significant correlation was found in natural scenarios however. As for preconception of noise reduction effectiveness, significant correlation of it with environmental impact reduction was only found in one of the eight scenarios, being positive at low level.

Table 4. Correlations of environmental impact reduction with aesthetic preference for barriers and with preconception of barriers' noise reduction effectiveness.

	Pearson's r							
	High traffic level				Low traffic level			
	100 m distance		300 m distance		100 m distance		300 m distance	
	Natural	Residential	Natural	Residential	Natural	Residential	Natural	Residential
Aesthetic preference	.190	.257*	.128	.237*	.153	.240*	.180	.270**
Preconception of effectiveness	-.009	.236*	.183	.134	-.130	-.038	-.009	-.088

* $p < .05$
** $p < .01$

4. Discussion

4.1. Are noise barriers always beneficial and how beneficial are they?

The results of this study show that noise barriers were always beneficial in mitigating environmental impact of motorways in varied traffic, distance and landscape scenarios where the effect of barriers were significant, which means that the positive effects of barriers, e.g., noise reduction and/or visual screening, always outweighed the negative effects, e.g., themselves as visual intrusion. In scenarios with low traffic level at 300 m, where the potential environmental impact of motorways was low, the effects of barriers became insignificant, which could either be that they had no perceivable positive or negative effect in such scenarios, or that their positive and negative effects were offset with each other and cancelled out. So while the targeted groups at shorter distances can benefit from barriers, those at far distances are not likely to suffer a decrease in environmental quality caused by the barriers.

As for how beneficial they were, the barriers did not show much advantage over tree belt, which was shown to be effective in reducing negative visual impact of motorways (Jiang et al., 2015), but did not offer any actual noise reduction and could even increase the possible noise impact by increasing people's sensitivity to the noise (Watts et al. 1999). The similar overall environmental benefits of berries and tree belt found in this study indicate the high importance of visual factors in mitigating environmental impact of motorways. Nevertheless, noise issue might still be the priority concern when traffic level goes high. In scenarios with high traffic levels in this study, some non- but nearly-significant results imply some tendencies that barriers offered larger reductions in environmental impact than tree belt did. Studies with wider ranges of participants are needed to further confirm these tendencies.

4.2. How do barriers of different characteristics differ in performance in varied scenarios?

While the tested barriers varied in size and transparency, they did not differ significantly in how effective they were generally over the eight environmental scenarios. They did show some differences in individual scenarios however. Again, some of the indicative differences were non- but nearly-significant and would require further examinations to draw more robust conclusions.

In terms of difference by barrier size, 5 m timber barrier seemed to perform better than 3 m timber barrier at 300 m but not at 100 m despite its larger noise reduction. This is probably due to the overwhelming visually intrusive and/or sight restricting effects of tall opaque barriers at close distances, and would support Highways Agency (2001b)'s general restriction on barrier height for avoiding visual intrusion. It might also be related to the degrees of visibility of the moving traffic, since Aylor & Marks (1976) has shown greater perceived loudness when noise source was totally obscured, and in this study, with the 5 m timber barrier at 100 m, moving traffic was totally invisible behind the barrier, while in other barrier and distance scenarios, moving traffic was always visible at low or high degrees.

In terms of performance difference by barrier transparency, there was no clear tendency over individual scenarios in this study. It seems though that 5 m transparent barrier was the least efficient barriers in most scenarios. This might be partly explained by the result found in Joynt & Kang (2010) that transparent barrier was perceived as less efficient than opaque barriers in noise reduction, and partly be explained by that while offering the same or higher noise reduction, transparent barrier reduced nearly no visual impact caused by moving traffic.

4.3. Are aesthetic preference and preconception of noise reduction effectiveness influential?

Aesthetic preference for barriers showed some positive correlations with the perceived barrier performance in this study. However, significant correlations were only found in residential scenarios. This might be related to the larger effect of barrier condition in residential scenarios than in natural scenarios as shown by the values of partial eta squared in Table 2, It might be explained by that natural landscape tends to be more vulnerable to visual intrusion and any barrier structure would be similarly deemed visually negative, while in residential landscape, barriers of different visual characteristics would be judged with larger variations. Positive contribution of aesthetic preference to overall performance of barriers was also found in Hong & Jeon (2014) which was in an urban context, while inversed contributions of preconception of noise reduction effectiveness was shown at difference noise levels, which shows some congruence with the generally insignificant correlations found between preconception of noise reduction effectiveness and barrier performance in this study. Overall, based on the results of these two studies, there is some confidence to say that aesthetic preference for barriers has potential positive influence on the perceived environmental performance of barriers especially in built-up areas, while the influence of preconception of noise reduction effectiveness is less clear.

5. Conclusions

This study aimed to investigate the overall performance of noise barriers in mitigating environmental impact of motorways, considering both of their acoustical and visual effects on perceived environmental quality, in various traffic, distance and landscape scenarios. Using computer-visualised video scenes and motorway traffic noise recordings, experimental scenarios, covering five barrier conditions, two traffic levels, two distances to road and two background landscape types, was presented to 30 participants of university students aged 19-27 for their subjective response in a laboratory experiment, although a wider range of participants may benefit this study for more significant results.

The results of this study show that noise barriers were always beneficial in mitigating environmental impact of motorways, or made no significant changes in environmental quality when the impact of motorways was low at far distance. The mitigation effect of barriers was only similar to that of tree belt which did not offer any noise reduction. But barriers did show some tendency to be more effective than tree belt when traffic level went high.

Barriers varying in size and transparency did not differ much in their overall performance over the experimental scenarios generally, although the transparent barrier tended to be the least effective in most scenarios. There seems to be some difference by barrier size at different distances however. Taller opaque barriers tended to perform better than shorter ones at far distance but not when getting closer despite their larger noise reduction, possibly due to their negative visual effect.

While no clear influence of preconception of barriers' noise reduction effectiveness was shown on perceived barrier performance in this study, Significant positive correlations were found between aesthetic preference for barriers and environmental impact reduction by barriers in residential scenarios, implying the importance of barrier aesthetic design when considering the overall environmental performance of the barriers.

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