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The efficacy of pink noise and earplugs for mitigating sleep disruption induced by different environmental noise sources

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ABSTRACT

Objectives: To investigate the efficacy of pink noise and earplugs in mitigating sleep fragmentation induced by intermittent environmental noise.

Methods: Twenty-five healthy adults (mean \pm SD age 28.5 \pm 5.9 years, 7 male) participated in a polysomnographic laboratory study with intermittent exposure to environmental noise (93 events; maximum sound pressure level 45 to 65 dBA), pink noise (40 or 50 dBA), foam earplugs, and their combination.

Results: Pink noise mitigated aircraft noise induced arousals and awakenings in a dose-response manner but was outperformed by earplugs. Awakening and arousal probability were highest for a crying baby and a fire alarm sound, followed by helicopter, low sonic boom, drone, rail, jet, and road noise.

Conclusions: Earplugs emerged as a more efficacious option for mitigating environmental noise effects on sleep disruption compared to pink noise. Noise legislation relying on jet noise studies likely underestimate the effects of helicopter noise and other emerging aircraft sounds on sleep.

Clinical Trial Registration: [ClinicalTrials.gov](https://clinicaltrials.gov), NCT05774977.

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Introduction

Large parts of the US population are exposed to nighttime aircraft noise, and several studies have shown that aircraft noise exposure disturbs sleep and impairs cognitive recuperation.^{1,2} Epidemiological studies show associations between environmental noise exposure and various long-term health consequences,^{3,4} which have also been associated with short, disturbed, or irregular sleep.⁵ Aircraft noise

can also trigger acute cardiac events during sleep contributing to cardiovascular mortality.⁶

Most studies of aircraft noise effects on sleep focus on jet noise, the most prevalent aircraft noise type around commercial airports.^{7,8} However, other types of aircraft noise with local concentration (e.g., helicopter noise) or with greater relevance in the future (e.g., drone noise, low sonic boom noise) are understudied and need investigation.

Effective countermeasures that are more affordable than sound insulation of buildings are needed to protect the population against aircraft noise effects on sleep. Broadband noise (BN), defined as noise whose power spectral density consists of a broad range of frequencies, is used by millions as an inexpensive, non-pharmacological sleep aid (often colloquially referred to as “white noise machines” or “white noise apps”), but research demonstrating its effectiveness is inconclusive.^{9,10} While there are several proposed

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What was known

Several studies have shown that traffic noise increases the likelihood of EEG arousals and awakenings from sleep and thus sleep fragmentation. Few studies address more than one traffic source which complicates comparisons across traffic sources.

What this study adds

This study investigates the effect of 11 different environmental sounds on sleep fragmentation with and without different noise countermeasures present. The study shows that the most frequently investigated type of aircraft noise, that is, jet noise, is associated with lower sleep fragmentation than helicopter, drone, and low sonic boom noise, with likely relevance for noise legislation.

mechanisms for the sleep promoting effects of BN, masking, that is, raising the threshold for perceiving one sound by introducing BN, is the most plausible.¹⁰ Earplugs are another affordable nighttime noise blocking intervention. Despite their widespread use, rigorous research on their effectiveness is largely missing and mostly addresses hospital noise.^{11,12} While the masking effect of BN and the attenuating effects of earplugs are desirable for many sounds, they are unwanted for sounds that are meant to alert us (e.g., a fire alarm or a crying baby).

To address some of the knowledge gaps outlined above, we performed a randomized, controlled, cross-over, polysomnographic sleep laboratory study in which we investigated the ability of pink noise (PN) and earplugs to mitigate the effects of intermittent environmental noise on sleep fragmentation. In addition to jet noise, we also investigated helicopter, drone, low sonic boom, road, and rail noise as common and emerging noise sources. Finally, we investigated to what extent PN and earplugs prevented arousals from sleep to a fire alarm sound and to a crying baby sound.

Methods

A detailed description of study methods can be found in Basner et al.¹³ Briefly, 27 healthy participants without sleep disorders or relevant hearing loss and naïve to broadband sound use during the night were enrolled in the study, and 25 (mean age \pm standard deviation 28.5 ± 5.9 years, range 21–41 years; 7 male) contributed to data analysis. The study protocol was approved by the Institutional Review Board of the University of Pennsylvania and participants provided written informed consent prior to participation. The study was registered at clinicaltrials.gov identifier NCT05774977.

This was a 7-night sleep laboratory study performed at the Chronobiology and Isolation Laboratory (CIL) in the Hospital of the University of Pennsylvania. Participants were investigated in seven groups of up to four. Planned lights out was 11 PM, and lights were turned on exactly 8 hours after lights out. Participants were allowed to leave the lab and pursue their normal activities during the day. They were, however, not allowed to nap, exercise, or drink alcohol during the day or consume caffeine after 3 PM. Adherence to these rules was verified with wrist-actigraphy and surveys.

After a noise-free adaptation night, participants experienced a sequence of the following six conditions: (1) Control night without noise exposure (CTRL); (2) environmental noise only (EN); (3) PN at 50 dBA only (PN50); (4) EN plus PN at 40 dBA (EN+PN40); (5) EN plus PN at 50 dBA (EN+PN50); (6) EN plus participants wearing standard foam earplugs (EN+EP; average earplug sound attenuation 25.5 dB). The conditions were presented on separate, alternating nights and followed a randomized sequentially counterbalanced Latin square design¹⁴ such that across study groups 1 through 6 each condition appeared in every night exactly once, and each condition was preceded by each other condition exactly once (i.e., ABCDEF; BDAFCE; CAEBFD; DFBEAC; EC-FADB; FEDCBA). Group 7 was a backup group, and its sequence was chosen in a way to optimally balance conditions across nights considering prior dropouts (CDEAFB; see Basner et al.¹³ for details).

For nights with EN playback (i.e., EN, EN+PN40, EN+PN50, and EN+EP), we selected nine traffic noise events (2 jets, 2 helicopters, 2

drones, 1 low sonic boom, 1 car, 1 train) and 2 alarm sounds (1 baby crying, 1 fire alarm). They were either recorded indoors or modified to reflect indoor noise exposure (partially open window). Noise event playback always started at the beginning of a full minute which coincided with the start of a 30-second sleep epoch. Noise events were played back multiple times at maximum sound pressure levels ($L_{AS,max}$) of 45, 55, and 65 dB, totaling 93 events across the night (see Basner et al.¹³ for rationale of choosing $L_{AS,max}$ and PN levels). PN playback started at lights out and was continuously played back throughout the night, while noise event playback started 15 minutes after lights out. Traffic noise events were spaced 4, 5, or 6 minutes apart. The sequence of noise event types, maximum SPLs, and noise-free intervals was randomized but balanced and identical across nights within a study group but changed across study groups. Noise was played back over speakers (JBL Control 47LP for PN and Neumann KH310A for noise events) and each room was calibrated to assure correct playback.

Overnight polysomnography (F3–C2, F4–C2, EOG–L, EOG–R, and EMG) was performed with the Cerebra Prodigy 2 system (Cerebra Health, Winnipeg, Canada). Supervised automatic sleep staging and electroencephalographic (EEG) arousal scoring was performed by the Siesta Group (Vienna, Austria). Periods with missing polysomnographic signals (5.5%) were excluded.

GEE repeated measures models with logit link function and AR(1) working correlation structure for biological plausibility were used for statistical analysis in SAS (Proc GENMOD, SAS Institute, Cary, NC; version 9.4). Clusters were defined at the subject-night level ensuring AR(1) was applied within nights only increasing the number of clusters from 25 to 120 with improved reliability of robust standard errors. Outcomes of interest were an EEG arousal (model 1) or an awakening (shift to stage wake; model 2) within 60 seconds (two epochs) after the start of a noise event (noise event duration averaged 38.2 seconds). If an arousal started before and ended after noise onset (model 1) or if a participant was awake prior to noise onset (model 2) the event was excluded from analysis. $N = 9527$ and $N = 9871$ noise events contributed to EEG arousal and awakening analysis, respectively. Predictors of interest included study night noise condition, $L_{AS,max}$, noise event type, study night, noise-free interval, prior sleep stage, elapsed sleep time, and participant sex and age (median split at 27 years). The CTRL condition was used as sham. Post-hoc contrasts were performed for AN+PN40, AN+PN50, and AN+EP vs. AN. p -values were adjusted for multiple testing with the false discovery rate method ($N = 33$ comparisons).¹⁵

Results

Regression results are shown in Table 1. Awakening and arousal probability decreased in the order EN, EN+PN40, EN+PN50, EN+EP, and sham, and was significantly lower compared to EN for all conditions but EN+PN40. Awakening and arousal probability significantly increased with event $L_{AS,max}$ and also differed significantly between noise event types. They decreased in the order alarm sounds (combined rank for awakenings and EEG arousals 1.5); helicopter (4); low sonic boom (4.5); drone (6.75); rail (8.5); jet (9.25); and road (10.5). Awakening and EEG arousal probability significantly differed depending on prior sleep

Table 1
Regression results for event-related analyses

	EEG arousals (N = 9527 events)		EEG awakenings (N = 9871 events)	
	Estimate (95% CI)	p-value	Estimate (95% CI)	p-value
Intercept	-1.0988 (-1.4442; -0.7534)	<.0001	-3.5707 (-4.1127; -3.0287)	<.0001
Noise condition		<.0001		<.0001
EN + PN40	-0.2051 (-0.4421; 0.0319)	.0899	-0.1545 (-0.4440; 0.1350)	.2956
EN + PN50	-0.3465 (-0.5989; -0.0940)	.0072	-0.3521 (-0.6531; -0.0512)	.0218
EN + EP	-0.7523 (-1.0170; -0.4875)	<.0001	-1.0838 (-1.4516; -0.7159)	<.0001
Sham	-0.9940 (-1.2434; -0.7445)	<.0001	-1.1903 (-1.5000; -0.8807)	<.0001
EN only (Ref.)				
Maximum SPL		<.0001		<.0001
65 dBA	0.7954 (0.6532; 0.9376)	<.0001	0.9931 (0.7973; 1.1888)	<.0001
55 dBA	0.2715 (0.1491; 0.3939)	<.0001	0.4261 (0.1942; 0.6580)	.0003
45 dBA (Ref.)	0		0	
Noise type		<.0001		<.0001
Crying baby	1.2327 (0.9786; 1.4868)	<.0001	1.9038 (1.5054; 2.3023)	<.0001
Fire alarm	0.9133 (0.6555; 1.1712)	<.0001	1.4148 (1.0006; 1.8290)	<.0001
Helicopter angled	0.5636 (0.3515; 0.7758)	<.0001	0.4323 (0.0654; 0.7992)	.0209
Helicopter leveled	0.5323 (0.2882; 0.7764)	<.0001	0.7104 (0.3107; 1.1100)	.0005
Low sonic boom	0.4919 (0.2830; 0.7009)	<.0001	0.601 (0.2529; 0.9491)	.0007
Drone fast	0.4394 (0.2337; 0.6450)	<.0001	0.4612 (0.0660; 0.8564)	.0222
Drone slow	0.3420 (0.1256; 0.5583)	.0020	0.2061 (-0.2037; 0.6159)	.3242
Jet Noise #1	0.1060 (-0.1041; 0.3160)	.3228	0.2886 (-0.0941; 0.6713)	.1394
Road Noise	0.0615 (-0.1745; 0.2975)	.6093	-0.0494 (-0.5124; 0.4135)	.8342
Rail Noise	0.0559 (-0.1686; 0.2805)	.6254	0.3749 (-0.0303; 0.7801)	.0698
Jet Noise #2 (Ref.)	0		0	
Age				
> 27 y	-0.1396 (-0.2798; 0.0006)	.0509	0.0043 (-0.1934; 0.2021)	.9658
≤ 27 y (Ref.)	0		0	
Sex				
Male	-0.1524 (-0.2925; -0.0123)	.0330	-0.0888 (-0.2877; 0.1100)	.3812
Female (Ref.)				
Study night		.6472		.4546
Night 7	-0.0043 (-0.2605; 0.2520)	.9739	0.2662 (-0.1239; 0.6563)	.1811
Night 6	-0.1195 (-0.3340; 0.0949)	.2746	-0.0015 (-0.3181; 0.3152)	.9928
Night 5	-0.1610 (-0.4289; 0.1070)	.2391	-0.1601 (-0.5008; 0.1807)	.3572
Night 4	-0.0396 (-0.2592; 0.1801)	.7240	0.0625 (-0.2373; 0.3622)	.6828
Night 3	0.0678 (-0.1784; 0.3141)	.5893	0.1267 (-0.1744; 0.4278)	.4094
Night 2 (Ref.)	0		0	
Noise-free interval		.4235		.9252
6 min	-0.0665 (-0.1946; 0.0616)	.3088	0.0224 (-0.1848; 0.2297)	.8319
5 min	-0.0797 (-0.2008; 0.0413)	.1968	-0.0169 (-0.2459; 0.2120)	.8847
4 min (Ref.)	0		0	
Prior sleep stage		<.0001		.0130
Stage N1	0.4054 (0.2241; 0.5867)	<.0001	0.4922 (0.1887; 0.7956)	.0015
Stage REM	-0.2276 (-0.408; -0.0472)	.0134	-0.1352 (-0.3465; 0.0762)	.2102
Stage N3	-0.4785 (-0.6286; -0.3284)	<.0001	-0.1595 (-0.3756; 0.0565)	.1478
Stage N2 (Ref.)	0		0	
Elapsed sleep time				
Hours	0.0248 (-0.0036; 0.0533)	.0869	0.0969 (0.0585; 0.1353)	<.0001

Estimates are on the logit scale (positive/negative values reflect increased/decreased arousal or awakening probability relative to reference or per unit, respectively). The PN50 night did not contribute to event-related analyses. EN: 93 environmental noise events; PN40: Pink Noise at 40 dBA; PN50: Pink Noise at 50 dBA; EP: Earplugs; Ref.: Reference Category; SPL: Sound Pressure Level; p-values next to category headings reflect type-III tests.

stage, decreasing from N1 to N2 to REM to N3. Male participants had a significantly lower EEG arousal probability compared to female participants. Awakening probability significantly increased with elapsed sleep time. None of the other variables investigated had a significant effect on awakening or arousal probability.

Quasi-likelihood under the Independence model criterion (QIC) values¹⁶ were nearly identical for AR(1) and Independence working correlation structures (4909.3 vs. 4909.2 for awakenings and 10,538.9 vs. 10,537.3 for arousals). Combined with small AR(1) alpha values (0.0148 for awakenings and 0.0769 for arousals), this confirms that residual within-night dependency was successfully absorbed by the fixed covariates elapsed sleep time, prior sleep stage, and noise-free interval.

Post-hoc tests contrasting the EN+PN and EN+EP conditions to EN alone showed that the mitigation of environmental noise effects on sleep fragmentation depended on event type (Fig. 1). Only earplugs were able to significantly mitigate the effects of EN on awakening probability for four event types (baby, fire alarm, helicopter with angled blades, and rail). For arousals, event types also included

helicopters with level blades, slow drones, and rail traffic. EN+PN50 significantly lowered arousal probability for the fire alarm only.

Discussion

This study investigated if and to what extent PN and earplugs were able to mitigate sleep fragmentation induced by intermittent environmental noise. PN significantly decreased the probability of aircraft noise induced awakenings and arousals in a dose-dependent manner. This sleep continuity promoting property of PN is likely due to masking,¹⁷ but, as we have shown before, PN also interferes with falling back to sleep in those who do wake up, especially during REM sleep.¹³ Earplugs outperformed PN40 and PN50 in preventing sleep fragmentation, and they do not interfere with falling back to sleep in those who do wake up. They were also well-tolerated and only one participant reported losing earplugs during the night.¹³ They thus emerged as the superior mitigation measure.

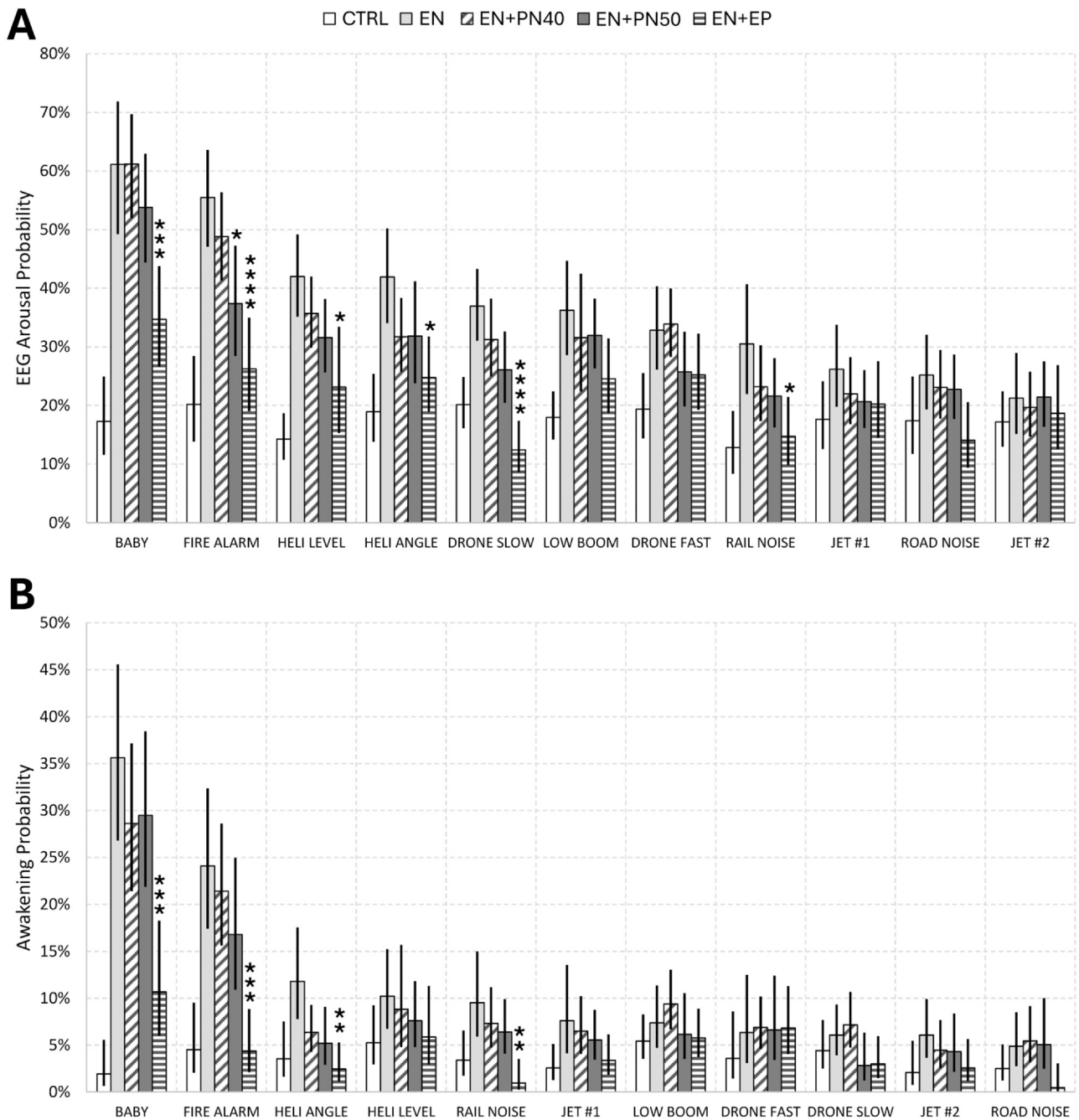


Fig. 1. Arousal probability (panel A) and awakening probability (panel B) by noise condition and event type. HELI ANGLE: helicopter with angled blades; HELI LEVEL: helicopter with level blades; DRONE SLOW: slow drone overflight; DRONE FAST: fast drone overflight. * $p < .05$; ** $p < .01$; *** $p < .001$; **** $p < .0001$ for contrasts of EN+PN40, EN+PN50, and EN+EP to EN (adjusted for multiple testing)

Awakening and arousal probability were highest for the crying baby and the fire alarm, which is unsurprising given that these sounds were designed to arouse (by nature or humans). Both PN and especially earplugs substantially reduced the likelihood of awakenings and arousals to these sounds, which can be problematic in situations when they warrant attention and waking up.

Arousals to traffic noise decreased in the order helicopter, low sonic boom, drone, rail, jet, and road noise. Past studies on the effects of aircraft noise on sleep have concentrated on jet noise.^{7,8} Our findings suggest that exposure-response functions based on jet noise likely underestimate the sleep disturbing effects of helicopter noise and the newly emerging drone noise and low sonic boom noise. This should be considered for noise legislation that aims at preventing the disruptive effects of aircraft noise on sleep.

Strengths of the study include the controlled laboratory environment and the balanced, cross-over, within-subject study design. To our knowledge, it is the first study to investigate the effects of helicopter, drone, and low boom sounds on objective measures of sleep. Limitations include the relatively small sample of healthy, young individuals. The findings may also not generalize to different kinds of BN (e.g., white noise), different noise levels (of both PN and EN), and chronic exposure situations. This study did not explicitly model the previously demonstrated¹⁸ inter-individual variability in noise sensitivity. Empirical standard errors exceeded model-based standard errors most notably for EN+PN40 and EN+PN50 nights, suggesting meaningful between-subject variability in the response to these combined noise conditions. More research is needed.

Ethical approval

All procedures were performed in compliance with applicable laws and institutional guidelines. Research was conducted under the governance of The University of Pennsylvania Institutional Review Board (protocol no. 852479).

Author contributions

Mathias Basner: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Michael G. Smith:** Conceptualization, Methodology, Software, Writing – review & editing. **Makayla Cordoza:** Conceptualization, Methodology, Writing – review & editing. **Matthew S. Kayser:** Investigation, Writing – review & editing. **Michele Carlin:** Conceptualization, Methodology, Investigation, Resources, Data curation, Writing – review & editing, Project administration. **Adrian J. Ecker:** Conceptualization, Methodology, Investigation, Resources, Data curation, Writing – review & editing. **Yoni Gilad:** Investigation, Resources, Data curation, Writing – review & editing. **Sierra Park-Chavar:** Conceptualization, Methodology, Investigation, Resources, Data curation, Writing – review & editing, Project administration. **Ka'alana Rennie:** Investigation, Resources, Data curation, Writing – review & editing, Visualization. **Victoria Schneller:** Investigation, Resources, Data curation, Writing – review & editing, Visualization. **Sinead Walsh:** Investigation, Resources, Data curation, Writing – review & editing. **Haochang Shou:** Conceptualization, Methodology, Validation, Formal analysis, Writing – review & editing. **Quy Cao:** Conceptualization, Methodology, Validation, Formal analysis, Writing – review & editing. **Magdy Younes:** Software, Writing – review & editing. **Daniel Aeschbach:** Conceptualization, Resources, Writing – review & editing. **Christopher W. Jones:** Conceptualization, Methodology, Validation, Investigation, Resources, Data curation, Writing – review & editing, Project administration.

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Declaration of generative AI and AI-assisted technologies in the writing process

The authors did not use generative AI or AI-assisted technologies in the writing process.

Data sharing

Public project data files are available via the National Transportation Library (NTL). Study documents and key results are publicly available via Clinicaltrials.gov (NCT05774977).

Declaration of conflicts of interest

The authors have no conflicts to disclose. Given their role as Senior Associate Editor, Mathias Basner had no involvement in the peer review of this article and has no access to information regarding its peer-review. Full responsibility for the editorial process for this article was delegated to another journal editor.

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