Minutes of the Gaines Charter Township Planning Commission

Special Meeting held April 15th, 2026, at 6 pm

South Christian High School Auditorium

7979 Kalamazoo Ave SE, Byron Center, MI 49315

MEMBERS PRESENT: Waayenberg**,** Rober, Thomas, Haagsma, Billips, Wiersema, Giarmo

MEMBERS ABSENT: None.

STAFF PRESENT: Dan Wells, Community Development Director; Dakota Swan, Assistant Planner; Rod Weersing, Township Manager; Cliff Bloom; Township Attorney

1. **CALL TO ORDER AND ROLL CALL**

   Chair Waayenberg called the meeting to order at 6:00 PM.

2. **CONSIDERATION OF MEETING AGENDA**

   The agenda was approved as presented.

3. **INQUIRY OF CONFLICT OF INTEREST**

   None.

4. **PUBLIC COMMENT**

Motion: comment	Motion by Wiersema, supported by Giarmo, to open the public period pertaining to any items not on the agenda.
DISCUSSION:	None.
AYES:	All
NAYS:	None
ABSTAIN:	None
DECISION:	Motion Carried (7-0)

An anonymous community member stressed that the Planning Commission works for the public rather than interest groups.

Leonna Church expressed that she is not supportive of the project and is disappointed by Steelcase's sale of the property.

Melinda Dumars, a resident who lives between 68th Street and 76th Street, urged the Planning Commission to address drag racing that occurs in the area.

Dave Duncan of 2105 76th Street reminded the Planning Commission that they work for the public.

John of 7644 Harmony Cove echoed previous concerns about traffic and high speeds, noting that 76th Street feels particularly dangerous.

Ashley, referring to the intersection of 60th Street and Kraft Avenue, reported that tall grass in the right-of-way is limiting visibility and causing safety concerns.

Tim VanDyke, who lives near 76th Street and Kalamazoo, echoed previous concerns about drag racing in the area.

An anonymous resident expressed similar concerns about traffic safety, citing a traffic death which occurred on Kalamazoo between 92nd Street and 100th Street.

Jason Boersema of Old Lantern Drive suggested that traffic lights on Eastern Avenue at 76th Street and 84th Street give better indication of 4-way-stops, specifically for the purpose of night driving.

Marcus Ringnalda expressed gratitude to the Township for a recent community open house to collect feedback on outdoor initiatives, noting that he is excited about increased recreational opportunities.
Andy Wyngarten of 8414 Kalamazoo Avenue expressed concern about the loss of farmland south of 84th Street.

Mark Apaldi of Hartman Drive reiterated earlier comments regarding traffic safety, specifically on 68th Street.

John, a Township resident of 30+ years, stated that the Gaines Marketplace area is “a mess”, and that he hopes the handling of this request goes smoother.

Keith, a resident of Cook’s Crossing, commented that there are a lot of great green spaces in the area, however, there are opportunities to make the area more bike-friendly.

Angela Rigas, State Representative for Michigan’s 79th District, shared earlier concerns about industrial traffic safety on 68th Street.

An employee of the local Target at 1925 Marketplace Drive expressed concern regarding the safety of the parking lot, specifically at night.

Stephanie Pratt of 4642 76th Street echoed earlier comments regarding traffic safety on 68th Street and 76th Street.

Laurie from Big Rapids referenced an instance in which members of the governing body in Big Rapids were recalled by members of the public.

Chloe from Grand Rapids urged the Planning Commission to "do better, be better".

Motion:	Motion by Giarmo, supported by Haagsma, to close the public comment period for any items not on the agenda.
DISCUSSION:	None.
AYES:	All
NAYS:	None
ABSTAIN:	None
DECISION:	Motion Carried (7-0)

5. ITEMS FOR CONSIDERATION

A. Public Hearing;

- **7147 Patterson Avenue, Conditional Rezone from Steelcase PUD-LSP to Light Industrial**
- **6900 East Paris Avenue, Rezoning from Steelcase PUD-LSP to Light Industrial**
- **4233 76th Street, 4367 76th Street, and 4645 76th Street, Rezoning from Agricultural/Rural Residential to Light Industrial**

Jonah Mills, Microsoft's Land Development Manager for this project, was joined by several other Microsoft representatives to offer an overview of the proposed rezoning. Mills stated that the application includes several rezoning conditions which will be enforceable by contract and zoning law. Microsoft has committed to investing in the community by preparing to enter a contractual agreement to hire local contractors, paying for long anticipated infrastructure upgrades, and dedicating a 9-acre piece of land to the Township for recreational purposes, said Mills. He added that Microsoft is also committed to using as little water as possible, and ensuring that residents will not experience rate increases on behalf of their project.

Mills stated that conditions outlined in the rezoning request address several requirements of the Zoning Ordinance and concerns brought up by the community, including sound, light, emissions, water use, decommissioning provisions, screening, and low vibrational sounds. The list of conditions also provides guidance for several matters not addressed in the Zoning Ordinance, indicating that Microsoft is committing to improvements and rules of conduct beyond what is required in the Zoning Ordinance. Mills noted that this is a very early phase in the project, however, Microsoft will do their best to answer any questions and collaborate with both the community and Township staff/officials.

Meredith Lizza, Microsoft's Community Affairs Manager, elaborated on Microsoft's commitment to the Township and desire to strengthen local partnerships. Lizza referenced instances of Microsoft's investment into other Midwestern municipalities, such as partnerships in Ohio and West Des Moines, Iowa, to fund wetland and habitat restoration, water quality improvements, and expand access and education across the community.

Dan Wells, the Community Development Director for Gaines Charter Township, shared an overview and assessment of the project. Wells discussed the proposed rezoning from Township staff's perspective, informed by standards and recommendations of the Gaines Charter Township Zoning Ordinance. Wells explained that this area of the Township has long been designated for industrial use and reiterated that the conditions included as part of this rezoning request set enforceable standards for several matters not directly addressed in the ordinance. Staff found that the application is consistent with the intent and recommendations of the 2023 Master Plan and satisfies all standards of review outlined in Chapter 31 of the Zoning Ordinance, "Zoning Amendment Review", and therefore endorse a positive recommendation of the rezoning request.

The Planning Commission then had the opportunity to ask Microsoft any questions before the public hearing began. Chair Waayenberg reminded the audience of the Planning Commission's role for this request, which is to make a recommendation to the Township Board of Trustees.

Commissioners Wiersema and Giarmo asked for clarification regarding the proposed condition on decommissioning. Wells offered further detail on the decommissioning clause, which intends to ensure that Microsoft will properly decommission and demolish any structures should the project falls through. Commissioner Thomas inquired about the financial burden of decommissioning, to which Township Attorney, Cliff Bloom, replied that Microsoft would be responsible for all decommissioning fees. Bloom noted that more details will be solidified as the Township's legal team and Microsoft's legal team work to finalize exactly which conditions will be included in the final conditional rezoning contract.

Motion:	Motion by Rober, supported by Haagsma to open the public hearing at 7:31 PM.
DISCUSSION:	None.
AYES:	All
NAYS:	None
ABSTAIN:	None
DECISION:	Motion Carried (5-0)

Jason Boersema expressed support for the project, stating that he would rather see this opportunity and growth happening here than elsewhere in the Midwest, citing this as a well-regulated investment.
John, a resident of Kent County, expressed concern and noted that although he is not necessarily anti-Microsoft, the Planning Commission has a lot to consider.

Molly, a resident on 76th Street stated that she does not believe residents will benefit from this investment and she is concerned about the loss of rural character.

Joe Davis of Caledonia said he is concerned about how the project will impact property values in the area.

Victoria Kane of 7049 Old Lantern Drive urged the Planning Commission to require any proposed data center to have a closed-loop system and use renewable energy.

Stacy of Caledonia expressed disapproval and noted that this proposal is different from the existing Switch facility, and requested adoption of a one-year moratorium.

Paul from Grand Rapids stated that he is concerned about power demand and Consumers Energy's ability to generate power.

Angela Rigas, State Representative for Michigan's 79th District, stated that she would like more information on the project and that she is a supporter of local decision-making.

Keith, a resident of Cook's Crossing and an IT professional, explained that he does not believe the existing Switch facility is an appropriate comparison for what Microsoft is proposing.

Tori from Grand Rapids expressed that she does not believe data centers are a light industrial use.

Jordan Chriswell, Township resident, expressed concern that Microsoft will not deliver on their promises, and supported the idea of a one-year moratorium.

John Hartwell, the union outreach coordinator for Operating Engineers Local 324, expressed support for the project as it would supply his skilled trades workers with employment and provide expanded opportunities for those in training.

Community member Sarah Lexo expressed concern regarding increases in water rates due to the project.

Daniel of Byron Center noted that he does not like the idea of potential pollution from the project.

Ryan, a representative for West Michigan Building trades, stated that Microsoft signed a contract with his organization, committing to employing local trades workers for the project should it come to fruition.

Christina Vissner of the Crystal Springs neighborhood expressed that she is concerned about the loss of nature, space, and potential health effects, specifically from sound exposure.

Chloe, a resident of the Township, expressed fear that the Planning Commission isn't representing the community's best interests but rather corporate interests.

Tim VanDyke, who lives near 76th Street and Kalamazoo, expressed concerns about the potential health effects of exposure to low vibrational noise, and noted that he doesn't believe fines are enough to hold Microsoft accountable.

Alex Gonzales, a resident of the Township, stated that he would like to see more research on the impacts of data centers to feel more comfortable, and expressed support for a one-year moratorium.

An additional IT professional who is a member of the community echoed previous concerns that Switch is not an adequate comparison.

Karin Sekelsky of Carpet Rose Drive said that she is concerned about risks to quality of life, and questions whose interests are being prioritized. She also expressed concern that the Township is lacking a noise ordinance.

Jeff, a resident of the Township, echoed previous concerns, specifically the lack of detail provided thus far on water use, wastewater, and power use.

Mark Lipaldi of Hartman Drive questioned why the public isn't able to vote on such a request, adding that he does not see much benefit to this project.

Thomas, a lifelong resident of West Michigan, shared that he fears how fast AI is advancing yet how little it is delivering on its promises, and added that he is concerned about increases in utility costs.

Liz Novak, a resident near 52nd Street and Kalamazoo Avenue, stated that she does not believe the Township stands a chance in court, should enforcement ever get to that point.

Tim Zandbergen of 4367 76th Street explained that the area in question was designated for industrial use several years ago, noting that a significantly more intense and obtrusive use could be proposed.

An anonymous resident of the Township who claimed to be an executive in data science for a Fortune 500 company stated that although in their industry, they do not support the project on behalf of environmental concerns.

Marcus Ringnalda, a 20-year resident of the Township, stated that he is supportive of the project as data centers are necessary and need somewhere to go, and he is worried about the impacts on future generations should this investment not be made in the Township.

David of the Steven's Pointe neighborhood expressed concern regarding potential environmental impacts from the project.

Travis of 5195 76th Street stated that him and his spouse are both healthcare professionals who are deeply concerned about the potential threats to quality of life associated with this project.

An anonymous resident echoed previous comments and added that they firmly believe Microsoft will prioritize profit over people.

Phi, a resident of the Township, expressed worries about his kids' future and stressed that he feels as though Microsoft is only concerned about profits.

Bill Hirsh of 8005 Breton Avenue stated that he has been farming in the Township for 35 years and is passionate about agriculture however he is concerned about losing farmland.

Cynthia Olson of 3925 Carpet Rose Drive stated that she recently spoke with Planner Wells and is disappointed that questions she posed during the conversation were not brought up during this meeting.

Dave Dunkin, a resident of the Township, expressed great concern regarding the loss of livestock and farmland, noting that he would like more clarity and concrete answers on the technology involved.

Mike Radley, who has a child that attends Dutton Elementary School, outlined the staff memo and highlighted potential deficiencies on which the Planning Commission could base a negative recommendation to the Township Board.

Tyler Gustman of 7081 Patterson Avenue said that he is not in support of the project and is worried given the close proximity of the land Microsoft owns to his property.

Stephanie Pratt of 4642 76th Street expressed concern over the proposed project, specifically that she does not believe a data center is a light industrial use, and voiced support for a one-year moratorium.

Jade Gustman of 7081 Patterson Avenue stated that she is worried about being able to sell her home, which is in very close proximity to the land Microsoft owns. She is also concerned about her well being impacted by construction.

Zach Abbott, a candidate running for State Representative in the 79th District, expressed concern regarding utility bill increases, noting that he chose to run on behalf of the affordability crisis.

Tom Leonard, candidate for Governor of Michigan, expressed that he is disappointed by the state subsidies and tax breaks that would be available to Microsoft at the state level.

Abigail, a resident of Dutton, stated that she is concerned about the wellbeing of future generations on behalf of this project, and noted that people have more power than money.

Brian, a resident of the Township, said that he is not in support of this project and is concerned about the lack of concrete evidence available for the Planning Commission to base their decision on.

David Johnson, a resident of the Township, stated that he came to the meeting open minded and didn't plan to speak, however after hearing previous testimonies, he is not supportive of the project.

Laurie, a resident of Big Rapids, shared testimony of a community effort in Big Rapids to recall and remove board members that were supportive of a proposed electric vehicle battery plant.

Scott of the Cherry Valley neighborhood in Caledonia posed the question of what about this proposal is in it for him, noting that Microsoft left him wondering what value they could add to his quality of life.

Sue of Copper Corner Drive stated that the Planning Commission deserves straight answers from Microsoft, and the public deserves straight answers from the Planning Commission.

A resident of the Township stated that construction jobs will be available regardless of what use is established on the property and expressed concerns regarding potential health effects.

Paula, a resident of Michigan, stated that she does not support the project, and shared information with the audience about organizing and getting involved in opposition initiatives.

Amanda, a resident who lives near 76th Street and Hanna Lake Avenue, stated that the light pollution emitted from Revolution Farms increases her concern for potentially obtrusive lighting at the Microsoft property.

A candidate running for State Representative in the 78th District stated that he plans to draft legislation that prohibits data centers from being built in Michigan, adding that they are "industrial parasites".

Christine, a resident of Cook's Crossing, expressed worries about water use and potentially toxic wastewater discharge.

Karina, a resident of the Township, expressed concern about high resource demand, and noted that the proposal from Microsoft appears to be vague, while advocating for a one-year moratorium.

Lucy, a high school student, expressed fear about AI stealing job opportunities, and stated that she would prefer to see an agricultural education center on the site where the project is being proposed.

Betty White, a fifth-generation Caledonia resident, reiterated previous concerns, highlighting that art is highly important to the human spirit and shouldn't be created by AI instead of humans.

Nicole Bukema, a prospective resident of Dutton, explained that her family is rescinding their plans to build a home in the area due to concerns about the proposed data center.

Kaitlyn, a senior environmental consultant from the Crystal Springs neighborhood, advised that the Township avoid the creation of a preventable problem and vote no on this request, rather than reacting and attempting to mitigate the issue after it has already manifested.

Cindy Forte of Carpet Rose Drive said that she is not supportive of the proposal and advocated for medical studies and a one-year moratorium.

A resident of the Township advocated against the proposed rezoning, specifying that this type of land use is inappropriate adjacent to residential areas.

A resident of Grand Rapids expressed concern regarding several things that people are using AI to replace, including therapists, teachers, lawyers, financial advisors, and relationships.

William of the Steven's Pointe neighborhood said that he is unsupportive of the project, specifically expressing concerns about corporate interests and potential impacts on the school across the street.

Shane Rieder of 7522 Carpet Rose Drive stated that he thinks the proposed park dedication Microsoft is offering is "kind of useless", and noted that he is concerned for his kids' wellbeing.

Kathy VanKuiken, a resident of the Township, expressed that she is unsupportive of the project and added that although some parcels are zoned as Light Industrial, she does not believe this project is a light industrial use.

Keith of 4410 76th Street strongly opposed the proposed rezoning and overall project, expressing concern regarding stormwater mitigation and advocating for a one-year moratorium.

Andy Wyngarden of 8414 Kalamazoo Avenue stated that he is not in favor of the project and is concerned about NDA's that have been dissolved, adding that Microsoft should be held accountable and required to pay for infrastructure upgrades.

A resident of the Township played audio from a data center reportedly located in Dowagiac, Michigan, and voiced strong opposition to the proposed rezoning.
Angela, a resident of the Township, said that public opposition to the project should be enough justification for the Planning Commission to make a negative recommendation.

Motion:	Motion by Haagsma, supported by Rober to close the public hearing at 10:31 PM.
DISCUSSION:	None.
AYES:	All
NAYS:	None
ABSTAIN:	None
DECISION:	Motion Carried (7-0)

Motion:	Motion by Haagsma, supported by Rober, to take a ten-minute recess.
DISCUSSION:	None.
AYES:	All
NAYS:	None
ABSTAIN:	None
DECISION:	Motion Carried (7-0)

Motion:	Motion by Haagsma, supported by Giarmo, to return to order at 10:42 PM.
DISCUSSION:	None.
AYES:	All
NAYS:	None
ABSTAIN:	None
DECISION:	Motion Carried (7-0)

Prior to deliberation, Chair Waayenberg noted that representatives for Consumers Energy and the Township Engineer were in attendance, should the Planning Commission have any questions pertaining to either.

Commissioner Haagsma said that he appreciates feedback received during the public hearing and highlighted some pieces of the rezoning contract that he believes need to be amended, such as decibel levels, decommissioning provisions, tax assessments, the proposed water system and water use, and enforcement provisions. Wiersema agreed and added low frequency sounds and vibrations.

Chair Waayenberg inquired about standard procedure for handling electronic waste; Mills responded that old technology gets recycled as much as possible and used in outreach programs or is otherwise properly disposed of. Giarmo expressed concern regarding wastewater protocol and water usage. Giarmo asked what guarantee there is that construction jobs will be sourced locally; Mills stated that

Microsoft was engaging with labor groups in the region prior to buying the land and is eager to work in Michigan as there is a historically strong labor force in the state.

Haagsma said that he would like to see more details regarding dewatering during construction, to which Mills responded that he can seek more information on this, noting that this is under the supervision of EGLE. Giarmo noted that she is most worried about noise that will be emitted from the project and asked whether a sound study will be conducted. Mills stated that Microsoft has conducted preliminary acoustic studies and they have initial estimates, but the final audible impact is uncertain until the site is laid out. Mills said Microsoft can provide more information at the next meeting and noted that there are several ways Microsoft approaches mitigating noise.

Commissioner Billips asked for further information on what Microsoft "paying their way" really looks like. Mills responded that when Microsoft enters into an agreement with a utility provider, they state their anticipated daily needs and pay up front for generation, transmission, and substations, if necessary. Billips also inquired about whether Microsoft has any evidence to support the claim that property values in the surrounding area wont be negatively impacted; Mills responded that internal discussions are ongoing on this topic, however, impacts to property values are highly variable depending on the context and geographic location.

Rober inquired about how power outages would impact Microsoft's operations: Mills responded that Microsoft would pay the infrastructure costs to improve the reliability of the grid and collaborate with local utility providers to alleviate stress on the grid. Rober also inquired about what the height of the buildings may be; Mills responded that they will be single-story, approximately 40 to 50 feet tall, but further detail will be provided during site plan review.

Haagsma expressed concern over the several unknowns associated with this application and stated he feels as though the Planning Commission is in a position to make a tabling motion. Attorney Bloom noted that the conditional rezoning agreement can be worked on and advised Microsoft to provide Township staff with any relevant additional information for any upcoming meetings.

Chair Waayenberg thanked those in attendance and said that this is still very early in the process.

Motion:	Motion by Haagsma, supported by Wiersema, to table the request for a conditional rezoning and allow Microsoft and Township staff to provide answers to concerns posed by the Planning Commission.
DISCUSSION:	Wiersema inquired and Mills elaborated further on the 9.5-acre park dedication, explaining that the site in question is still being evaluated and Microsoft is looking for other opportunities to invest in the community. Wiersema inquired about a potential discrepancy regarding the parcels involved, specifically one ending in -007 that he wasn't able to find on the Kent County GIS viewer. Microsoft's legal counsel clarified

CERTIFICATION:

I hereby certify that the above is a true copy of the minutes from the April 15th, 2026, Planning Commission Meeting of the Gaines Charter Township Planning Commission held at the time and place mentioned above pursuant to the required statutory procedures.

Respectfully submitted,

Lani Thomas

Lani Thomas,

Secretary

Gaines Charter Township Planning Commission

Date: May 28, 2026

From:	Rebecca Klanderman
To:	Rebecca Klanderman
Subject:	FW: Microsoft Data Center Opposition Letter
Date:	Monday, April 13, 2026 4:59:18 PM
Attachments:	image890454.png

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Gain More
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Rebecca Klanderman
Receptionist
Administrative Assistant
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From: Nicole Buikema <nbuikema.15@gmail.com>
Sent: Tuesday, April 7, 2026 1:26 PM
To: Kim Triplett <Kim.triplett@gainestownship.org>; danwells@gainestownship.org; Dakota Swan <dakota.swan@gainestownship.org>; Michael Brew <Michael.Brew@gainestownship.org>; Bob Terpstra <Bob.terpstra@gainestownship.org>; Rod Weersing <rod.weersing@gainestownship.org>; Laurie Lemke, MiCPT, CPFA <laurie.lemke@gainestownship.org>; Kim Triplett <Kim.triplett@gainestownship.org>
Subject: Microsoft Data Center Opposition Letter

I would like this letter as public record in preparation for the April 15 meeting. Please confirm receipt.

Hello,

My name is Nicole Buikema. My family and I are (or were) building a house next to Dutton Elementary. We were very excited to move to Caledonia from Grand Rapids, and my 6 year old daughter was ecstatic that she would be able to walk to school-- how cool!

The planned Microsoft data has completely upended our plans. I cannot in good conscience move my family (including two little girls) to a property so close to a massive data center. I am astonished and honestly furious that these plans have been moving forward next to a brand new elementary school.

Hyperscale data centers are new. There are no long term studies on the health effects for children who are located within a quarter mile. This is incredibly shortsighted and dangerous for these kids. Will the air quality be so bad some days they have to stay in for recess? Will their water be contaminated? Will the noise be so irritating that it causes headaches or attention loss? Will kids develop asthma? migraines? What about long term health impacts? We don't know what will happen. We don't know because there are no other cases yet. The not knowing should be enough for us to take pause, to put our kids first.

Another impact of these hyperscale data centers being so new is that there is very little state and federal regulation around them to keep communities safe. We cannot be so gullible to take large corporations who are trying to make a profit at their word.

As I mentioned we were planning on moving into the Dutton school district, but unless the data center plan changes we will not be moving. We are one example, but what does this do for the community. The Dutton Elementary school is beautiful, it had to be a huge undertaking and is a pride point for the area-- Not anymore. Not if there is a 350+ acre data center across the street. This is scaring away families who are ready to invest in and be part of the community. This will scare longstanding members of the community away.

I focused mainly on the school and the kids, but there are so many impacts that are truly scary and not being considered. Data centers are creating heat islands, raising the temperature of the surrounding area by an average of 16 degrees (CNN). They raise utility bills, they use an incredible amount of water, they create constant light and noise pollution.

There are very few positives and a mountain of negatives. Please oppose the data center altogether. Please do not consider rezoning the remaining acres that Microsoft has purchased, and at minimum please consider a 1 year moratorium to allow legislation to catch up with businesses.

Thank you,

--
Nicole Buikema
c: 231.624.6349

December 16, 2025

Gaines Township Planning Commission
8555 Kalamazoo Avenue SE
Caledonia, MI 49316

Dear Gaines Township Planning Commission:

As a resident of Gaines Township, I strongly oppose the rezoning request by Microsoft for the parcel located at 7147 Patterson Avenue SE, Caledonia, Michigan 49316 (hereinafter the "Parcel"). As detailed below, Microsoft's rezoning request does not meet the requirements of the Zoning Amendment Approval Standards in § 31.40 A of the Township's Zoning Ordinance. Additionally, if the Planning Commission approves this request, it will cause irreparable harm to the community and environment.

I will address portions of the Zoning Amendment Approval Standards under § 31.40 A of the Township's Zoning Ordinance in turn below.

2. The rezoning of the land will not negatively impact adjacent and nearby property:

a. The allowable land uses within the proposed zoning district are compatible with nearby land uses and zoning districts.

The Report submitted by Dan Wells, Community Development Director (hereinafter the "Report"), states that the rezoning request meets the standard for this requirement. However, the Report fails to state in this section that the properties located to the east of the Parcel are zoned as rural residential.

Pursuant to the Township's Zoning Ordinance § 12.10 A, a light industrial zone "should have . . . significant separation and buffering from residential areas." A buffer, at a minimum, is "[a] strip of land which provides visual separation and aesthetic relief between potentially incompatible uses or provides protection to natural resources through the use of landscaping, preservation of existing vegetation, berms, or screening, or a combination of materials." Zoning Ordinance § 35.10. Significant separation is not defined under the Zoning Ordinance, but it can be assumed to mean a greater distance than abutment.

Microsoft's Addendum to its Rezoning Application (hereinafter the "Application") notes that a "set of residential lots [are located] to the east of the property." Their Application tries to dismiss this issue by saying that "[t]he majority of those are in Caledonia Township and separated from the subject parcel by Patterson Avenue. Only two residential lots abut the property."

The Zoning Ordinance is clear that a light industrial parcel requires "significant separation and buffering from residential areas." § 12.10 A. Unlike Microsoft implies, there is no distinction in the law between a few residential properties or many. Residential properties that share a property line with a light industrial property would directly violate the zoning law as they would not be "significantly separated." § 12.10 A. Furthermore, Patterson Avenue does not qualify as a buffer between a light industrial zone and a residential zone. By definition, a buffer is a "strip of land" and separates areas through "landscaping, berms, preservation of existing vegetation, or screening." Zoning Ordinance § 35.10. An asphalt road, Patterson Avenue specifically, does not fall under the definition of a buffer as it is not vegetation, landscaping, a mound of dirt, etc.

Overall, the Report and Application fail to address the residential properties that are adjacent to the Parcel. When those residential properties are considered, rezoning the Parcel would be in violation of the Zoning Ordinance's requirements for significant separation and buffers between light industrial areas and residential areas.

b. There will be no adverse physical impact on surrounding properties.

Unlike the Report and Application state, there will be adverse physical impacts on surrounding properties. Microsoft and the Mr. Wells are again ignoring the residential properties that abut the Parcel and the community at large.

The Zoning Ordinance prohibits any activity from emitting "vibration" that "will adversely affect permitted used on an adjacent property" or activity that "emit[s] noise that is readily discernable to the average person in any adjacent residential zoning district." § 18.160 A and B. The Township's Master Plan further states that "[i]ndustries that traditionally cause excessive noise, vibration, odors, visual blight, environmental pollution, or are[] involved in potentially hazardous processes, should be avoided or allowed only on a discretionary basis." Master Plan, Page 55.

Data centers are notorious for their 24/7 buzzing noises and vibrations caused by their cooling systems.[1] The noise pollution from data centers impacts the physical health of people by causing permanent hearing loss, severe migraines, nausea, and even panic attacks.[2] Data Centers also adversely impact the environment by scaring away wildlife with their noises, causing

[1] https://www.npr.org/2025/07/17/nx-s1-5469933/virginia-data-centers-residents-saying-no.
[2] https://www.aipowerweekly.com/p/how-bad-are-the-health-effects-of.

significant pollution through the use of fossil fuels to meet their tremendous electricity demands, and using up between hundreds of thousands up to millions of gallons of water per day.[3]

Allowing the Parcel to be rezoned for a light industrial use for a data center violates the Zoning Ordinance's prohibitions on noise, vibrations, and environmental pollution and is inconsistent with the Township's Master Plan.

c. There will be no adverse effect on property values in the adjacent area.

Mr. Wells confidently claims in his Report that the parcel's development by Microsoft will "increas[e] values over the long term." Even Microsoft in its Application does not make this bold claim. In fact, Microsoft argues that "[a]ny impact on property values would have already occurred."

Developing the Parcel into a data center will likely have an impact on property values, particularly the residential properties that both abut and are located across the roadway from the Parcel. However, data centers are relatively new, and there is not enough long-term data to make a sound determination if there will or will not be adverse effects on property values in the adjacent area.

Without further information, it cannot be claimed that Microsoft meets the Zoning Ordinance's standard here.

d. It will not create a deterrent to the improvement or development of adjacent property in accordance with existing regulations.

Mr. Wells claims in his Report that "[r]ezoning [the Parcel] to Light Industrial will have no effect on future development of the parcels to the west and south, as they are identical and compatible in use." However, yet again, Mr. Wells is ignoring that the parcels to the east of the Parcel are residential properties. Developing the Parcel into a data center will create a deterrent to improve or develop the adjacent residential parcels.

As data centers cause signification noise and environmental pollution, individuals near the Parcel would likely want to leave, not improve, and/or not develop the adjacent residential properties.

3. The site is adequately served by streets and public utilities, and the rezoning will not impact the delivery of public services.

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[3] https://www.bbc.com/news/articles/c93dnnxewdvo; https://www.staxengineering.com/stax-hub/the-environmental-impact-of-data-centers/.

As stated earlier, data centers use tremendous amounts of water. A large data center can use up to five million gallons of water per day.[4] This incredible amount of water usage leads to depleted water resources which harms the community and environment at large.[5] Michigan is already in a drought, and the state's watersheds are at risk of depletion.[6] Our community's and state's water supply would be at risk if this Parcel is rezoned and a data center is built on it.

Additionally, data centers use colossal amounts of electricity. In 2024, data centers located in the United States collectively used more electricity than the entire country of Pakistan.[7] The electricity consumed by data centers significantly strains the power grid and causes unreliability.[8] Across the United States, data centers have already caused numerous power outages, and that risk is only increasing.[9] A data center in our Township may strain the power grid and cause power outages.

Based on this information, if the Parcel is rezoned, the data center cannot be adequately served by public utilities and will impact the delivery of public services.

In conclusion, rezoning the Parcel is inconsistent with the Township's Zoning Ordinance. Additionally, the proposed data center would significantly and irreversibly harm the community and environment. As such, the Planning Commission should deny Microsoft's request to rezone the parcel located at 7147 Patterson Avenue SE, Caledonia, MI 49316 to light industrial.

Respectfully,

Jordan Chrispell
Attorney and Gaines Township Resident
2921 Valley Spring Drive
Caledonia, MI 49316

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4 https://www.eesi.org/articles/view/data-centers-and-water-consumption.

5 https://www.npr.org/2022/08/30/1119938708/data-centers-backbone-of-the-digital-economy-face-water-scarcity-and-climate-ris.

6 https://www.theguardian.com/technology/2025/dec/16/great-lakes-us-data-centers; https://droughtmonitor.unl.edu/CurrentMap/StateDroughtMonitor.aspx?MI.

7 https://www.pewresearch.org/short-reads/2025/10/24/what-we-know-about-energy-use-at-us-data-centers-amid-the-ai-boom/.

8 https://www.pewresearch.org/short-reads/2025/10/24/what-we-know-about-energy-use-at-us-data-centers-amid-the-ai-boom/.

9 https://www.reuters.com/technology/big-techs-data-center-boom-poses-new-risk-us-grid-operators-2025-03-19/.

From:	Dakota Swan
To:	Rebecca Klanderman
Subject:	Public Comment FW: Concerning the Data Center
Date:	Thursday, March 19, 2026 9:36:31 AM
Attachments:	image001.png

GAINES CHARTER TOWNSHIP
Gain More
www.gainestownship.org
dakota.swan@gainestownship.org

Dakota Swan*(she/her)*
Assistant Planner
Office: 616-698-6640 Ext. 119
Cell: 616-893-1760

From: Dakota Swan
Sent: Thursday, March 19, 2026 9:36 AM
To: 'Taylor Freund' <freund.taylor@gmail.com>
Cc: Dan Wells <dan.wells@gainestownship.org>
Subject: RE: Concerning the Data Center

Good morning Taylor,

Thank you for these additional comments. We will be sure to provide this feedback to the Planning Commission.

Sincerely,

GAINES CHARTER TOWNSHIP
Gain More
www.gainestownship.org
dakota.swan@gainestownship.org

Dakota Swan*(she/her)*
Assistant Planner
Office: 616-698-6640 Ext. 119
Cell: 616-893-1760

From: Taylor Freund <freund.taylor@gmail.com>
Sent: Thursday, March 19, 2026 9:30 AM
To: Dakota Swan <dakota.swan@gainestownship.org>
Cc: Dan Wells <dan.wells@gainestownship.org>
Subject: Re: Concerning the Data Center

Hi Dakota,

I wanted to write to express my concerns once more, since Microsoft is moving forward with buying more land for a data center, about the large scale data center in Kent County, specifically Gaines township. As a resident of Kent County I am NOT in favor of a project like this. Any bit of research into the impact on surrounding areas to data centers show immensely increased electrical expenses paid on the part of the residents, as well as pollution concerns (how many times have big companies like this promised eco-friendly measures, only to fail us again and again for short term profit yielding?) and of course the impacts to our water table.
Please have it noted that this household is NOT in favor of inviting this big corporation into my township. It is not in favor of the people you represent; you do not have our consent. I ask that you do not invade and occupy our neighborhood without our consent.

Taylor Freund

On Mon, Dec 29, 2025, 12:46 PM Dakota Swan <dakota.swan@gainestownship.org> wrote:

> Hello Taylor,
>
> Thanks for your comments; they will be provided to the Planning Commission for consideration.
>
> Sincerely,
>
> GAINES CHARTER TOWNSHIP
> Gain More
> www.gainestownship.org
> dakota.swan@gainestownship.org
>
> **Dakota Swan***(she/her)*
> **Assistant Planner**
> Office: 616-698-6640 Ext. 119
> Cell: 616-893-1760
>
> ---
>
> **From:** Taylor Freund <freund.taylor@gmail.com>
> **Sent:** Monday, December 29, 2025 12:29 PM
> **To:** Dakota Swan <dakota.swan@gainestownship.org>
> **Subject:** Concerning the Data Center
>
> Hi Dakota,
>
> I hope the holidays find you well. I wanted to write to express my concerns about the

large scale data center in Kent County, specifically Gaines township. As a resident of Kent County I am NOT in favor of a project like this. Any bit of research into the impact on surrounding areas to data centers show immensely increased electrical expenses paid on the part of the residents, as well as pollution concerns (how many times have big companies like this promised eco-friendly measures, only to fail us again and again for short term profit yielding?) and of course the impacts to our water table. Please have it noted that this household is NOT in favor of inviting this big corporation into my township. It is not in favor of the people you represent; you do not have our consent. I ask that you do not invade and occupy our neighborhood without our consent.

Regards,
Taylor Freund

Cathy L. Gorniewicz
3754 76th St. SE
Caledonia MI

I would like this statement to be put on the record about the Microsoft rezoning project.

Large areas in the State of Ohio already have the same data centers. The people living in those ares are not happy about the air quality and ground pollution caused by the data centers which effect water, plants, animals (domestic and wildlife), and humans. The effects include hearing loss, psyche disorders, and other long term health disorders. They use millions of gallons of water every 3-5 years. Seven data centers?...having 140 generators, 140 cooling systems and 280 fans. Where will they get the millions of gallons of water from?...ground water or huge water towers. The data centers collect data on the people in Ohio. In the Army we used what is called intelligence listening devices.

Tracts of land (including farmland) is being lost for housing construction and now data centers. Our local park was recently "improved" by increasing the parking area and

over

replacing the beautifully designed bridge going over the creek in the park with a unimaginative, plain bridge. Many people disaproved of your plan but you did it anyway.

Water. Where are the millions of gallons used by the microsoft project going to go? In the ground? In the air? In plaster creek? Pollute the ground, pollute the air, and the creek also? Can't help but wonder. I would like for council mimbers to actually, some day, work for our community. Thank you for your Time.

Cathy L. Gorm

From:	Dan Wells
To:	Rebecca Klanderman
Subject:	Fw: Request for Careful Review of Proposed Microsoft Data Center Rezoning
Date:	Monday, April 6, 2026 7:58:09 AM
Attachments:	image360398.png

GAINES CHARTER TOWNSHIP
Gain More
www.gainestownship.org
dan.wells@gainestownship.org

Dan Wells
Community Development Director
Office: 616-698-6640 Ext.120
Cell: 616-980-6188

From: Tricia Mullins <tmullins742@gmail.com>
Sent: Friday, April 3, 2026 9:45 PM
To: Dan Wells <dan.wells@gainestownship.org>
Subject: Request for Careful Review of Proposed Microsoft Data Center Rezoning

Greetings,

I respectfully ask that this message be shared with the Gaines Charter Township Planning Commission for their consideration as part of the rezoning review.

Dear Gaines Charter Township Board Members: Connie Giarmo, Ronnie Rober, Lani Thomas, Tim Haagsma, Brad Waayenberg, Ryan Wiersema, and Talimma Billips

I am writing regarding the proposed rezoning request for the Microsoft data center planned near 7147 Patterson Ave SE. While I do not live within Gaines Charter Township, I have been following this proposal closely because of its potential regional impacts on shared water resources, air quality, and infrastructure systems, which extend beyond township boundaries.

I listened to the public comments from the most recent Board meeting and found the concerns raised by residents thoughtful and reasonable. Speakers discussed the scale of the proposed facility, including the number of cooling systems and diesel generators, potential long-term water and wastewater considerations, and the likelihood of ongoing noise. Others noted that communities across the country are still learning about the long-term impacts of large data centers, particularly when they are located near residential areas.

I was also struck by comments regarding the proximity of the proposed site to nearby neighborhoods and schools. Even from a regional perspective, these are issues that deserve careful review, transparency, and thorough analysis before zoning decisions are finalized.

Given the size and permanence of this project, I respectfully encourage the Board to proceed cautiously and ensure that all potential impacts are fully understood and publicly addressed before moving forward.

Thank you for your time and for your service to the community.

Sincerely,

Tricia Mullins
Charlotte, MI

March 16, 2026

Gaines Charter Township Zoning and Planning Commission

8555 Kalamazoo Ave., SE Caledonia, MI 49316

RE: Formal Opposition to Microsoft rezoning

To the Members of the Gaines Charter Township Zoning and Planning commission,

I am writing to formally register my opposition to the proposed rezoning of the property at **7147 Patterson Avenue Caledonia, MI 49316.** As a resident of **Caledonia** for **10** years, I have carefully reviewed the current local ordinances and the potential impacts of this proposal.

My opposition is based on the following specific points of conflict with existing regulations and community standards:

- **Non-Compliance with Zoning Ordinance, Chapter 1 :** My research indicates that the proposal violates **section 1.20** which states the purpose of the ordinance is to “promote public health, safety, and welfare”, “ensure that uses of land are situated in appropriate locations”, “preserve and protect environmental resources” . The current plan does not meet the requirements for this by placing seven Ai data centers in this location. These data centers are known to cause serious irreversible health problems in humans and animals. This land is situated less than one mile from Dutton Elementary School, 2 horse farms, and it is surrounded by residential and agricultural properties. These data centers will require a massive volume of **5–15 million gallons of water** to fill closed-loop cooling systems across seven buildings, as stated by Microsoft representatives. Every 3–5 years, this entire volume—5–15 million gallons—will be discharged into the city sewer system as industrial waste and then completely replenished. This cycle represents an extraordinary and unnecessary strain on our municipal water infrastructure and local water tables, which is contrary to the ordinance's purpose to 'preserve and protect environmental resources.

Precedent and Character: Allowing this would set a problematic precedent for the **Dutton/Caledonia** area, undermining the protections established in **Zoning Ordinance, Chapter 1: Intent, section 1.20** “ensure that uses of land are situated in appropriate locations”.

I request that the Board deny this proposal or, at minimum, postpone a decision until a comprehensive independent impact study is conducted and shared with the public. I request that the Board considers a moratorium to make time to amend the current ordinances to add specific guidelines for data centers to protect the safety and wellbeing of the neighboring residents.

Please include this letter in the official public record for the upcoming meeting scheduled for Microsoft. I look forward to your response regarding how the Board intends to address these specific regulatory conflicts.

Sincerely,

Stephanie Pratt

4642 76th ST SE Caledonia, MI 49316

616-890-1584/stephalynn81@att.net

March 19, 2026

Gaines Charter Township Zoning and Planning Commission

8555 Kalamazoo Ave., SE Caledonia, MI 49316

RE: Formal Opposition to Microsoft rezoning

To the Members of the Gaines Charter Township Zoning and Planning commission,

I am writing to formally register my opposition to the proposed rezoning of the property at **7147 Patterson Avenue Caledonia, MI 49316.** As a resident of **Caledonia** for **10** years, I have carefully reviewed the current local ordinances and the potential impacts of this proposal.

My opposition is based on the following specific points of conflict with existing regulations and community standards:

- **Impact on the environment :** Based on a study completed by the University of Michigan Ford School of Science, Technology, and Public Policy, this change would lead to enormous energy, and water demands, contrary to the goals outlined in **the master plan future land use page 55**. This states "industrial uses to be promoted will include manufacturing and transport operations with minimal impact on the environment or on the surrounding community"**.** It also states "industries that traditionally cause excessive noise, vibration, odors, visual blight, environmental pollution, or area involved in potential hazardous processes should be avoided".
- **Non compliance with zoning ordinance, Chapter 15: Land use, section 15.30** "if a use is not specifically listed anywhere in this ordinance and is not determined to be virtually identical to any other specifically listed uses, the use is prohibited". The ordinance does not specify "use of data center".

I request that the Board deny this proposal or, at minimum, postpone a decision until a comprehensive independent impact study is conducted and shared with the public. I request that the Board considers a moratorium to make time to amend the current ordinances to add specific guidelines for data centers to protect the safety and wellbeing of the neighboring residents.

Please include this letter in the official public record for the upcoming meeting scheduled for Microsoft. I look forward to your response regarding how the Board intends to address these specific regulatory conflicts.

Sincerely,

Stephanie Pratt

4642 76th ST SE Caledonia, MI 49316

616-890-1584/stephalynn81@att.net

March 21, 2026

Gaines Charter Township Zoning and Planning Commission

8555 Kalamazoo Ave., SE Caledonia, MI 49316

RE: Formal Opposition to Microsoft rezoning

To the Members of the Gaines Charter Township Zoning and Planning commission,

I am writing to formally register my opposition to the proposed rezoning of the property at **7147 Patterson Avenue Caledonia, MI 49316.** As a resident of **Caledonia** for **10** years, I have carefully reviewed the current local ordinances and the potential impacts of this proposal.

My opposition is based on the following specific points of conflict with existing regulations and community standards:

- **Non compliance with zoning ordinance, Chapter 18:** my research indicates that the proposal violates **section 18.160** which states "no permitted activity shall emit or produce odor, fumes, dust, glare, or vibration", "no permitted activity shall emit noise that is readily discernible to the average person in any adjacent residential zoning district", "no permitted use shall discharge effluent of any kind onto or into the ground or in violation of sewage treatment regulations", "any permitted activity that may present a danger of fire, and explosions shall not represent any danger to property or persons behind property line". Microsoft stated at the open house that each building (total 7) will have multiple (20-25) backup generators (filled with diesel fuel), and multiple (20-25) cooling systems (filled with glycol and other chemicals) which produce odor, fumes, vibrations and noise. Microsoft admits all the equipment including back up generators, and cooling equipment make so much noise it requires sound mitigation. **This admission of 'mitigation' confirms a violation of Section 18.160, as the noise is inherently 'discernible' to the average person if mitigation is required.**

- **Impact of Devaluation of Neighboring Properties: LAWFUL NONCONFORMITIES, Chapter 33: GENERAL CHANGES, RE-ESTABLISHMENT, AND SUBSTITUTION, section 33.20 Substitution of a Lawful Nonconforming Use:** “additional standards shall be met, and the proposed use shall: a. Be as compatible as or more compatible with the surrounding neighborhood; b. Not have a substantially detrimental effect on the use and enjoyment of adjacent uses or properties; c. Not negatively impact public health, safety, and welfare; d. Not result in traffic safety concerns; and e. Not cause a serious impact on the natural environment”.

I request that the Board deny this proposal or, at minimum, postpone a decision until a comprehensive independent impact study is conducted and shared with the public. I request that the Board considers a moratorium to make time to amend the current ordinances to add specific guidelines for data centers to protect the safety and wellbeing of the neighboring residents.

Please include this letter in the official public record for the upcoming meeting scheduled for Microsoft. I look forward to your response regarding how the Board intends to address these specific regulatory conflicts.

Sincerely,

Stephanie Pratt

4642 76th ST SE Caledonia, MI 49316

616-890-1584/stephalynn81@att.net

From:	Dan Wells
To:	Rebecca Klanderman
Subject:	Fw: Here is proof from Microsoft in Wisconsin regarding noise complaints
Date:	Tuesday, March 31, 2026 4:14:45 PM
Attachments:	image507234.png

GAINES CHARTER TOWNSHIP
Gain More
www.gainestownship.org
dan.wells@gainestownship.org

Dan Wells
Community Development Director
Office: 616-698-6640 Ext.120
Cell: 616-980-6188

From: Stephanie Maleport <stephalynn81@att.net>
Sent: Tuesday, March 31, 2026 3:43 PM
To: Michael Brew <Michael.Brew@gainestownship.org>; Kim Triplett <Kim.triplett@gainestownship.org>; Bob Terpstra <Bob.terpstra@gainestownship.org>; Laurie Lemke, MiCPT, CPFA <laurie.lemke@gainestownship.org>; Rod Weersing <rod.weersing@gainestownship.org>; Dan Wells <dan.wells@gainestownship.org>; Kim Triplett <Kim.triplett@gainestownship.org>; Dakota Swan <dakota.swan@gainestownship.org>
Subject: Here is proof from Microsoft in Wisconsin regarding noise complaints

Good afternoon,

Please watch this video from Mount Pleasant Wisconsin about the neighbors of Microsoft with the "new technology". This is only ONE of "fifteen or more" data centers they are building there.

I am going to ask you again, PLEASE do NOT make this our reality. Microsoft hasn't responded to the neighbors there. Is that a "good neighbor"?

I want this video to be part of the public record for that Microsoft zoning meeting on April 15th, 2026. I will be submitting an opposition letter as well. Please confirm receipt of this email.

Thank you,

Stephanie Pratt
4642 76th ST SE
Caledonia, MI 49316
616-890-1584

Video link:

https://youtu.be/gc5XZJfF0kQ?si=lw0EIEz5fbi5-M6a

From:	Dan Wells
To:	Rebecca Klanderman
Cc:	Rod Weersing; Dakota Swan
Subject:	Fw: Research articles for Microsoft meeting
Date:	Tuesday, April 14, 2026 8:08:57 AM
Attachments:	image334195.png

Good Morning Rebecca,

Please PDF all these and go ahead and package all the comments received so far. We'll email them to the Planning Commissioners.

GAINES CHARTER TOWNSHIP
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www.gainestownship.org
dan.wells@gainestownship.org

Dan Wells
Community Development Director
Office: 616-698-6640 Ext.120
Cell: 616-980-6188

From: Stephanie Maleport <stephalynn81@att.net>
Sent: Monday, April 13, 2026 5:37 PM
To: Kim Triplett <Kim.triplett@gainestownship.org>; Bob Terpstra <Bob.terpstra@gainestownship.org>; Michael Brew <Michael.Brew@gainestownship.org>; Rod Weersing <rod.weersing@gainestownship.org>; Dan Wells <dan.wells@gainestownship.org>; Laurie Lemke, MiCPT, CPFA <laurie.lemke@gainestownship.org>; Dakota Swan <dakota.swan@gainestownship.org>; Kim Triplett <Kim.triplett@gainestownship.org>
Subject: Research articles for Microsoft meeting

Good evening,

I am sending links to many research articles about noise and the effects on adults and children. I am sending a link about asthma and air pollution as well. Please have everything included in the public record for the Microsoft Meeting on Wednesday, April 15.

https://www.researchgate.net/publication/8436730_Vibroacoustic_disease

https://pubmed.ncbi.nlm.nih.gov/37564480/

https://www.frontiersin.org/journals/medicine/articles/10.3389/fmed.2026.1751843/full

https://pubmed.ncbi.nlm.nih.gov/38195479/

https://www.sciencedirect.com/science/article/pii/S0160412021005304?ref=pdf_download&fr=RR-2&rr=9ebd8edd9e3eaef5

https://www.researchgate.net/publication/390626274_The_Impact_of_Noise_on_Learning_in_Children_and_Adolescents_A_Meta-Analysis

https://www.biorxiv.org/content/10.64898/2026.03.26.714563v1.full.pdf

https://www.readcube.com/articles/10.3389/fclim.2026.1648912

https://journals.sagepub.com/doi/10.1177/00139165241245823

Please confirm receipt of this email.

Thank you,

Stephanie L. Pratt BSN RN CNOR

Environment International 158 (2022) 106905

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Noise pollution and human cognition: An updated systematic review and *meta*-analysis of recent evidence

Rhiannon Thompson [a,b], Rachel B. Smith [a,b,c], Yasmin Bou Karim [a,b], Chen Shen [a,b], Kayleigh Drummond [a,b], Chloe Teng [a,b], Mireille B. Toledano [a,b,c,d,e,*]

[a] *Department of Epidemiology and Biostatistics, School of Public Health, Imperial College London, UK*
[b] *MRC Centre for Environment and Health, School of Public Health, Imperial College London, UK*
[c] *Mohn Centre for Children's Health and Wellbeing, School of Public Health, Imperial College London, UK*
[d] *National Institute for Health Research Health Protection Research Unit (NIHR HPRU) in Environmental Exposures and Health, School of Public Health, Imperial College London, UK*
[e] *National Institute for Health Research Health Protection Research Unit (NIHR HPRU) in Chemical and Radiation Threats and Hazards, School of Public Health, Imperial College London, UK*

A R T I C L E I N F O

Handling Editor: Paul Whaley

Keywords:
Cognition
Noise pollution
Systematic review
Meta-analysis

A B S T R A C T

Background: This systematic review provides a comprehensive synthesis of recent epidemiological evidence that environmental noise negatively impacts human cognition.
Methods: We update a prior review with recent publications (PROSPERO CRD42019151923). The strength of evidence for associations was assessed using the GRADE (Grading of Recommendations, Assessment, Development and Evaluations) framework. We also conducted random-effects *meta*-analyses where suitable.
Results: 16 studies were identified and reviewed in tandem with 32 studies previously reviewed by Clark & Paunovic (2018). A *meta*-analysis from 3 studies found that reading comprehension scores in quiet classrooms were 0.80 (95% confidence interval: 0.40; 1.20) points higher than children in noisier classrooms. Meta-analysis of the impact of 1 dB (dB) increase in environmental noise on reading and language abilities gave a pooled beta coefficient of −0.11(95% confidence interval: −0.32; 0.10). A *meta*-analysis of Odds Ratios (OR) from 3 studies found higher odds of cognitive impairment in people aged 45 + with higher residential noise exposure (OR 1.40, 95% CI: 1.18;1.61). After qualitative synthesis of remaining studies, there was high quality evidence for an association between environmental noise and cognitive impairment in middle-to-older adults, moderate quality evidence for an association between aircraft noise and reading and language in children, and moderate quality evidence against an association between aircraft noise and executive functioning in children. Generally the literature was supportive for other cognitive outcomes, but with low or very low-quality evidence.
Discussion: The evidence so far suggests that noise exposure is associated with cognition, but more good quality research using standardised methodology is required to corroborate these results and to allow for precise risk estimation by larger *meta*-analyses. There is also a need for more research with older teenagers and young-to-middle aged adults, on the synergistic effects of noise and air pollution, and in Africa, Central and South America, South Asia and Australasia.

1. Introduction

Environmental noise exposure ('noise pollution') is a key global public health concern, with implications for physical health, wellbeing, and mortality (Basner et al., 2014, Clark and Paunovic, 2018b, Basner and McGuire, 2018, Van Kempen et al., 2018). Noise pollution is pervasive in many areas containing human populations, arising from transport, industry, and community activity (e.g. technology, machinery, nightlife). People can be exposed to excess noise at home, school, work, and other settings, and whilst noise exposure can disrupt concurrent activities and performance (Hughes and Jones, 2001, Szalma and Hancock, 2011) there are additional concerns that noise, as an environmental exposure, can carry overall risks for human health and development beyond any immediate interference.

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E-mail address: m.toledano@imperial.ac.uk (M.B. Toledano).

https://doi.org/10.1016/j.envint.2021.106905
Received 8 June 2021; Received in revised form 21 September 2021; Accepted 23 September 2021
Available online 12 October 2021

Cognition refers to the faculties involved in acquiring, processing, using, and producing information and understanding, and includes attention, memory, learning, memory, executive function, reasoning, computation, and language (Harvey, 2019). Cognitive ability is not only related to academic achievement but also health, success, mental health, and wellbeing as a whole (Batty et al., 2007, Bortolato et al., 2015, Bukodi et al., 2014). Environmental noise exposure is thought to affect the brain and cognition due to its detrimental effects on the learning process (e.g. distracting attention from lessons or work), sleep (e.g. keeping one awake and affecting cognitive capability and development subsequently), stress (increasing psychological frustration and annoyance, and physical stress responses involving cortisol and adrenaline), and learned helplessness (a noisy environment impacting the individual's sense of control and self-efficacy, reducing their confidence and motivation) (Basner et al., 2014, Hahad et al., 2019, Hatfield et al., 2002, Hume et al., 2012, Stansfeld and Clark, 2015).

A previous review synthesised the evidence for cognitive associations with noise across the lifespan prior to June 2015 (Clark and Paunovic, 2018a). However, this review did not *meta*-analyse the evidence and only research on children was identified by Clark & Paunovic in their search up to June 2015. Further, their search was for a broad range of sources of environmental noise (e.g. neighbourhood noise, wind turbine noise, residential noise) but the focus of the literature up to 2015 had been on the effects of transport noise. The prior review was updated in brief in 2020 (up to March 2019) but due to the broader focus of that review (Evidence for Environmental Noise Effects on Health for the United Kingdom Policy Context) it did not have a detailed analysis of the different cognitive faculties as outcomes nor any *meta*-analysis (Clark et al., 2020), leaving a gap for such a review of recent evidence. As Clark and Paunovic's review focussed upon general population cognitive outcomes, rather than clinical outcomes with cognitive symptoms, and as more recent reviews have summarised this evidence (Hegewald et al., 2020, Paul et al., 2019, Szalma and Hancock, 2011), the focus of this review was on cognitive abilities measured in the general population rather than medical diagnoses or symptoms.

Therefore the objective of this study is to provide an updated review of the literature and evaluation of the evidence base that will inform policy and practice to tackle noise pollution. The PECOS (participants, exposure, control/comparison, outcomes, and study design) statement for this research is as follows:

- Participants: human populations across the lifespan,
- Exposure: environmental noise (exposure to noise in day-to-day life, as opposed to noise presented in a lab to measure concurrent effects on cognition).
- Control/Comparison: persons less exposed (continuously or in high/low exposure groups)
- Outcomes: non-pathological cognitive abilities
- Study Design: epidemiological study designs- cohort, case-control and observational studies.

2. Methods

This review was registered on PROSPERO prior to commencing (CRD42019151923). It has been written in accordance with the PRISMA-P checklist for reporting systematic reviews and *meta*-analyses (Shamseer et al., 2015).

2.1. Update strategy

Using the AMSTAR 1 (A Measurement Tool to Assess Systematic Reviews) and ROBIS (Risk Of Bias In Systematic reviews) methodologies for assessing quality of systematic reviews (Whiting et al., 2016, Shea et al., 2007), we assessed the review by Clark & Paunovic (2018a) to be of sufficient quality to update rather than repeat their work (see supplementary materials for assessment). Thus, the search was limited to those studies published after June 2015 (when Clark & Paunovic's search took place). We based our search terms upon theirs and used their identified studies prior to June 2015 in our quantitative and qualitative syntheses. Clark and Paunovic's search terms included non-environmental noise such as 'noise from personal electronic devices OR noise from mp3 players' but the focus of their review was on environmental noise rather than personal exposure through specific leisure activities so we followed this strategy and excluded such sources.

2.2. Search strategy and eligibility criteria

The online databases EMBASE (Ovid), PubMed, PsychINFO (ProQuest) and Web of Science were searched for epidemiological studies of the relationship between noise exposure across the lifespan (including prenatal period) and human cognitive functioning assessed across the lifespan. This did not include clinical outcomes with cognitive symptoms such as ADHD and dementia. Search terms and strategy can be found in supplementary materials. These searches were conducted on 26/09/2019 and on 14/07/2021 by title/abstract. Grey literature was considered and included if a full research article of the results was not available elsewhere. Reference lists of studies were also scanned for any further literature.

The eligibility criteria were as follows:

1. Studies could report any measured performance indicative of cognitive function (e.g. performance on neurocognitive tasks, academic skills, global IQ, measures of neurodevelopment, cognitive decline).
2. Noise exposure only included the estimated real-life day-to-day environmental noise exposure (e.g. traffic noise, aircraft noise, Day–evening–night noise level (Lden) in decibels (dB), equivalent continuous sound level in dB (LAeq), night-time noise in dB (Lnight)) and not experimental manipulations of noise measuring concurrent cognition.
3. Publications written in English, as there were not sources available for translation

2.3. Review process

Two independent reviewers (RT and YBK in 2019, RT and CT in 2021) carried out the search and screened titles, abstracts, then full texts, against eligibility criteria. Any disagreements as to paper eligibility were resolved by an independent third reviewer (RBS). Studies excluded after the initial title screening are listed with reasons in supplementary materials (C). Reviewers independently extracted the fields Title, Authors, Year, Study location, sample size, age, gender, study design, exposure, exposure period, method of exposure assessment, cognitive outcome, measure of cognitive outcome, confounders measured and adjusted for, statistical analysis conducted, outcome/results, conflict of interests and funding. Where a publication was not available through institutional access, it was requested from authors.

2.4. Risk of bias and quality of evidence assessment

The OHAT Risk off Bias Rating Tool was used to evaluate risk of bias across the following six domains: selection bias (were participants a representative sample who are comparable across exposure levels?); confounding bias (were key socioeconomic covariates and possible other exposures controlled for?); attrition bias (low levels of exclusion or attrition, or demonstration it should not appreciably bias results); exposure characterisation (was the characterisation of noise a valid approach?); outcome characterisation (was the characterisation of cognition a valid approach?); and publication bias (were all measured outcomes and planned analyses reported in results?). Ratings of 'definitely high', 'probably high', 'probably low', and 'definitely low' risk of bias were applied in duplicate and agreed between two reviewers, with criteria for the ratings from OHAT Risk of Bias Rating Tool for Human and Animal Studies (NTP, 2015). The specific criteria for each rating for each domain are provided in supplementary materials (C). The ratings for each field by paper are provided in the main summary Tables 1 and 2.

These fields were then used in application of the GRADE methodology for evaluating the overall quality of evidence for different cognitive outcomes (Morgan et al., 2016). In accordance with OHAT Approach for evidence integration, the initial GRADE confidence was based upon the following key features of the study design (moderate confidence for 3 features, low for 2 features, very low for 1 feature); exposure prior to outcome (longitudinal evidence), individual outcome data, comparison group used (or participant outcomes compared over a range of continuous exposure), or controlled exposure, which did not arise in this review due to its focus on observational epidemiological evidence (Rooney et al., 2014). Evidence for associations could then be downgraded on the basis of Risk of Bias concerns (ascribed when $\geq$ 50% of studies rated 'probably high' or 'definitely high' risk of bias in 2 + Risk of Bias domains) imprecision of effects, inconsistency, indirectness, and publication bias. Finally, ratings could be upgraded if all plausible confounders or other biases increase confidence in the observed effect, if a large or very large effect was observed, or a dose–response gradient was observed. All GRADE quality of evidence decisions and reasons are specified in Table 3.

As Clark & Paunovic did not specify the exact Risk of Bias assessment results for individual studies (only across groups of studies), it was not possible to establish the impact of the addition of new literature without re-applying the same domains across new and previously reviewed literature. We therefore re-assessed the risk of bias for Clark & Paunovic's studies such that our GRADE assessments were applied equivalently across old and new literature. To assess publication bias, funnel plots were produced of the different statistical estimate types which could be extracted from the literature across cognitive outcomes.

2.5. Meta-analysis

All outcomes and exposures from identified studies and studies included in the prior systematic review (Clark and Paunovic, 2018a, Clifford et al., 2016) were considered to identify effects which (i) reflected valid measurements of the same aspect of cognition, (ii) did not come from overlapping study populations, and (iii) had compatible (the same or computable) effect statistics, performing *meta*-analysis if 3 effects met these criteria. If further details were required from authors to perform *meta*-analysis these were requested. Mean differences and pooled standard errors were computed from separate group estimates. DerSimonian and Laird's inverse-variance, random effects models was estimated using the package "meta" in R version 3.6.1 (Balduzzi et al., 2019, Core, 2019).

3. Results

We identified 2817 records in the initial searches, which after exclusions left 16 studies to be included in the qualitative synthesis (see Fig. 1) The level of agreement on paper selection between the first two reviewers was high (Cohen's Kappa 0.94 (95% CI: 0.88–1).

Although Clark & Paunovic (2018) report that 34 studies were selected for their review, 32 studies are referenced, discussed, and included in their summary of studies table. All 32 studies involved children, usually with noise exposure being measured at schools, although their inclusion criteria were across the lifespan. Most (80%) of the studies were cross-sectional and 80% raised risk of bias concerns, which is consistent with Clark and Paunovic's suggestion of further good quality research being required.

We identified a further 16 studies on the associations between environmental noise exposure and cognition, which included 12 in adults (1 in young adults, 4 in adults of all ages, and 7 in older or middle-to-older adults) (Table 1), 3 in children/adolescents, and 1 in babies. There were more longitudinal studies, however a large proportion of the recent literature raised some risk of bias concerns (88%).

Across the previously identified and new literature, there were 13 studies from the USA, 29 from Europe, 4 from Asia, 2 from (South) Africa, 0 from Central and South America, and 0 from Australasia. Characteristics of these individual studies and their risk of bias in the domains specified in the OHAT are summarised in Tables 1 (Novel literature) and 2 (previously reviewed literature).

3.1. Children and adolescents

3.1.1. Academic performance

We identified one study investigating noise exposure and performance on standardised academic tests, which found that children at low noise exposed schools had better task completion and test scores on reading and maths tests compared to children at high-noise exposed schools; covariates were not controlled for although authors state this was a homogenous sample (Papanikolaou et al., 2015). Prior to June 2015, Clark and Paunovic identified 11 papers on this subject (Cohen et al., 1973, Cohen et al., 1981a, Cohen et al., 1981b, Eagan et al., 2004, Green et al., 1982, Haines et al., 2002, Lukas et al., 1981, Pujol et al., 2014, Sharp et al., 2014, Shield and Dockrell, 2008, Zusman, 2007). This evidence supported an association but was low quality for traffic noise and very low quality for aircraft noise.

3.1.2. Reading, verbal, and language ability

This review includes two studies on noise exposure, one observing that aircraft noise exposure was associated with reading comprehension in German school children (Klatte et al., 2017) and the other found that high measured noise exposure at school was associated with worse performance on a reading task (Papanikolaou et al., 2015). Secondary analysis of the data presented by Klatte et al. (2017) presented at conferences (not peer-reviewed) reported that teacher-assessed classroom distraction by aircraft noise mediated this relationship, and that both daytime LAeq and NAT60 (Number of Aircraft noise events > 60 dB(A)) independently contributed (Spilski et al., 2017a, Spilski et al., 2017b). Clark and Paunovic discussed 16 studies on noise exposure and reading/linguistic abilities (Bronzaft, 1981, Bronzaft and McCarthy, 1975, Clark et al., 2012, Clark et al., 2013, Clark et al., 2006, Cohen et al., 1973, Haines et al., 2001a, Haines et al., 2001c, Haines et al., 2001b, Hygge et al., 2002, Klatte et al., 2014, Matsui et al., 2004, Seabi et al., 2012, Seabi et al., 2015, Stansfeld et al., 2010, Stansfeld et al., 2005).

A *meta*-analysis of 6 effect sizes, extracted from 3 studies, reflecting mean differences in reading test scores between noisy and quiet classrooms (either rail or aircraft noise, Fig. 2) found significantly higher scores in quieter classrooms (by 0.80 points, 95% CI: 0.40;1.20) with significant heterogeneity ($p < .001$). TE refers to the treatment effect of individual studies (here the difference in mean reading test scores), and seTE refers to the standard errors of treatment effects. In noisy classrooms, the average Leq was 59–69.9dBA, and Max Leq 89–96.5, whereas in low noise exposed classrooms the average Leq was 54.4–57 dBA and Max Leq 73.2–74.3. The authors applied different reading tests, therefore this is not a precise estimate of how noise relates to reading but does reflect a trend in the literature which is supportive of an effect. A *meta*-analysis of beta coefficients (Fig. 3) from linear regressions of noise (mixed sources) upon reading/writing test performance also found a trend of noise reducing abilities although it did not reach significance (-0.11, 95% CI: −0.32;0.10), with significant heterogeneity (<0.01). Different tests of outcome were also applied by these authors, therefore this again indicates the trend of the literature rather than precisely estimating dose–response.

Overall the qualitatively and quantitatively synthesised literature was supportive of an association of total (mixed noise), aircraft noise, rail noise, and apartment noise with reading/language skills, with moderate, moderate, very low, and very low-quality evidence respectively. The literature was not supportive of a relationship between traffic noise and reading/language abilities, with low quality of evidence.

3.1.3. Attention

Clark and Paunovic identified 12 studies of noise and attention in children (Cohen et al., 1973, Cohen et al., 1981a, Cohen et al., 1981b, Haines et al., 2001a, Haines et al., 2001c, Hygge et al., 2002, Lercher et al., 2003, Matsui et al., 2004, Sanz et al., 1993, Stansfeld et al., 2010, Stansfeld et al., 2005, Van Kempen et al., 2010), which were supportive of associations with attention for aircraft and traffic noise exposure, with one study finding evidence against an effect of railway noise on attention.

Since 2015, a study of residential traffic noise in children did not observe any relationship with performance on the attention network task (Julvez et al., 2021). However, a study observed a relationship between noise levels measured at home and sustained attention in babies (Wass et al., 2019). Overall the quality of evidence was low, very low, very low and very low, for relationships between attention and aircraft, traffic, railway and home noise exposure respectively, but it was potentially more supportive of sustained attention than others components of attention.

3.1.4. Executive function

9 studies identified by Clark & Paunovic evaluated noise and executive function, which were overall not supportive of an effect (Clark et al., 2012, Haines et al., 2001a, Haines et al., 2001b, Klatte et al., 2014, Matheson et al., 2010, Stansfeld et al., 2010, Stansfeld et al., 2005, Van Kempen et al., 2012, Van Kempen et al., 2010). Similarly, a more recent longitudinal study did not observe a relationship between executive function and residential traffic noise levels in children (Julvez et al., 2021). The GRADE assessed quality of overall evidence (for the lack of a relationship between noise and executive function) was moderate for aircraft noise, and low for traffic noise.

3.1.5. Memory

Our review did not identify any studies on environmental noise exposure and memory, but Clark and Paunovic found 12 studies (Clark et al., 2012, Haines et al., 2001a, Haines et al., 2001b, Hygge et al., 2002, Klatte et al., 2014, Lercher et al., 2003, Matheson et al., 2010, Matsui et al., 2004, Stansfeld et al., 2010, Stansfeld et al., 2005, Van Kempen et al., 2012, Van Kempen et al., 2010) which suggested overall a negative effect for aircraft and rail noise but not an association with traffic noise, with low, very low, and very low quality evidence respectively.

3.1.6. Fluid intelligence

One large longitudinal study evaluated the relationship between residential traffic noise exposure and fluid intelligence (performance on the Ravens Coloured Progressive Matrices test (CPM) and observed no relationship in 6–11 year olds, but more good quality research is needed to be conclusive.

3.2. Adults

According to Clark and Paunovic (2018a) they not identify any studies of noise exposure and adults' cognitive abilities when conducting their search in June 2015, but this review identifies 12 studies published since then.

3.2.1. Academic ability

One study of students in Thailand found that noise annoyance was not associated with worse Grade Point Average (GPA), but self-reported impact on reading and mental tasks by noise was associated with worse GPA in off-campus students. Onchang and Hawker reported that measured noise exposure levels were higher in off-campus students, who also had lower GPA, but they did not present/conduct any analysis of association between measured noise level and GPA (Onchang and Hawker, 2018). This evidence is therefore very low quality. The age group (average age 21) could also be considered an adolescent group by some definitions (Sawyer et al., 2018).

3.2.2. Maths and literacy

Gao and colleagues (Gao et al., 2021) observed significant negative longitudinal associations between performance on literacy and mathematics questions and traffic noise in adults (range unspecified, median age 48.38). This single study constitutes low quality evidence.

3.2.3. Attention

Another study of Navy Personnel in Norway found that after controlling for a variety of covariates, measured noise at work (>77.1 dB(A) compared to < 72.6 dB(A)) was associated with worse attentional abilities, but it was a very small sample (Irgens-Hansen et al., 2015). Further, another study found that high industrial noise exposure to workers in the metal industry (higher than 85 dB(A)) was associated with worsened attention, whereas a group doing similar work under quieter conditions (lower than 80 dBA) did not show the same decline in ability (Zeydabadi et al., 2019). This evidence is suggestive of relationships between workplace noise and attention, however with very low quality evidence supporting this due to risk of bias concerns.

3.2.4. Memory

Zeydabadi and colleagues (2019) observed worse performance on the Wechsler memory test in workers exposed to industrial noise higher than 85 dB(A) compared to below 80 dB(A). However, in a higher quality longitudinal study of older adults, long-term residential noise was not associated with episodic memory (Weuve et al., 2021) which was replicated in a cross-sectional study of 45–74 year olds (Crous-Bou et al., 2020).

3.2.5. Cognitive impairment

In the German SALIA cohort, contemporaneous traffic noise exposure in the day was associated with total CERAD-plus cognitive function score, and with its figure copying sub-task (Fuks et al., 2019), and there was a threshold-dependent effect of night time traffic noise on figure copying. In another study of older people in Germany, day time (but not night time) noise exposure 3–7 years previously was associated with mild cognitive impairment with and without amnesia (Tzivian et al., 2016b) but not continuous cognitive score (Tzivian et al., 2016a). However, noise and global cognitive score were related in this cohort when air pollution exposure was high, suggesting they may act synergistically to impact cognition in older adults (Tzivian et al., 2017). IN another study of older people in the USA, a 10 dB(A) increase in residential noise was associated with 36% higher odds of mild cognitive impairment. In a similar sample, each 12 dB(A) increase in residential noise exposure was associated with a 30% higher risk of cognitive impairment (with or without dementia) in older people (Yu et al., 2020). Finally, a study of adults in South Korea observed 11% higher odds of subjective cognitive decline in people who self-reported noise pollution in their residential area (Ju et al., 2021).

A *meta*-analysis of 3 Odds Ratios (Fig. 4), reflecting the impact of higher residential noise on the odds of cognitive impairment in people aged 45 + found significantly higher odds with higher noise exposure (1.40 points, 95% CI: 1.18;1.61) with non-significant heterogeneity (p = 0.75). Noisier residences either had 10 dB(A) higher weighted 24-hour mean noise levels than quieter reference addresses, or had mean noise levels of 50–73.8 dB(A) relative to 30.5–49.9 dB(A). Cognitive impairment (without dementia) was identified using the CERAD-plus, MMSE, a general cognitive battery, and physician assessments. Differences in definitions of exposure mean we do not have a precise estimate (e.g. dose–response, a threshold) for how noise relates to cognitive impairment but this does suggest higher noise levels are associated with increased risk of cognitive impairment. This literature tends towards supporting a relationship between traffic noise and cognitive impairment in middle-to-older aged people, and the evidence is of high quality, but it does suggest a complex picture as some effects were dependent on the presence of air pollution.

Table 1
New literature identified in this systematic review.

Author and year	Analytical sample: n, age (μ and σ unless stated otherwise), gender, location	Measurement of exposure	Measure of cognition	Confounders considered (controlled for or demonstrated unrelated)	Outcomes- most adjusted model *p < .05	Risk of bias: Selection bias	Confounding bias	DH: Definitely High PH: Probably High PL: Probably Low DL: Definitely Low: Attrition/ Exclusion bias	Exposure characterisation	Definitions of DH, PH, PL, DL found in supplementary materials (C): Outcome characterisation	Selective reporting bias
Fuks et al., 2019	N = 288 Age 67–80 (mean 74.5 ± 2.2), 100% female, Germany	Modelled traffic noise at residence in 2006; weighted 24-h mean (Lden, range 30.5–73.8 dB (A)) and night-time mean (Lnight, range 21.7–63.5 dB (A)) as well as self-reported noise annoyance	The CERAD-Plus (Consortium to Establish a Registry for Alzheimer's Disease) *Cognitive functions implicated in Alzheimer's Disease*	Age, smoking, ETS, depression (self-report), air pollution (ESCAPE LUR-PM and NO2 at residence), education, noise annoyance	Lden ≥ 50 dB(A) and probability of lower than average figure copying OR 2.72 (95% CI 1.44, 5.12) and total score 1.69 (0.94, 3.04). Lnight ≥ 40 dB(A) and lower than average figure copying OR 2.27 (1.09, 4.72), noise annoyance appeared to be associated with *better performance on* Boston naming test and figure copying.	PH	PL	PH	PL	DL	DL
Gao et al., 2021	N = 15,163, Age 48.38, 49.72% female, China	Average traffic noise) in prefecture-level city (metric unspecified), median 68, Q1 67, Q3 68.3 (presumably dB).	Standardised verbal and math tests from China Family Panel Studies (CFPS)	Age, gender, urban–rural area, years of education, annual income, marital status, smoking, drinking, race, city, temperature	Traffic noise exposure significantly negatively associated with individuals' verbal test scores (1 year exposure beta −0.295, 2 years −0.296, 3 years −0.316, 4 years −0.313, all p < 0.01) and math test scores (1y −0.147, 2y −0.149, 3y −0.161, 4y −0.173, all p < 0.01).	PL	PL	DH	PH	PL	PL
–	N = 958, Ages 45–74 (mean age 57.0 ± 7.0), 63.9% female, Barcelona	Modelled daily noise level at street nearest to residence, at night (Lnight) and total noise level (Lden). Total noise	Outcome composite scores based on Memory Binding Test (immediate and delayed recall), WAIS-IV coding, & semantic fluency. *Global cognition,*	Age, gender, years of education, BMI, smoking status at baseline, physical activity, self-reported diabetes status,	mPACC cognition & episodic memory composites not associated with Lnight or Lden. Executive function trend effect: β = 0.63 for total	DH	PL	PH	PL	DL	DL

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Table 1 (*continued*)

Author and year	**Analytical sample:** **n, age (μ and σ unless stated otherwise), gender, location**	**Measurement of exposure**	**Measure of cognition**	**Confounders considered (controlled for or demonstrated unrelated)**	**Outcomes- most adjusted model *p < .05**	**Risk of bias**		**DH: Definitely High PH: Probably High PL: Probably Low DL: Definitely Low**		Definitions of DH, PH, PL, DL found in supplementary materials (C)	
						Selection bias	**Confounding bias**	**Attrition/ Exclusion bias**	**Exposure characterisation**	**Outcome characterisation**	**Selective reporting bias**
		mean 67.3 dB (SD 5.52)	*episodic memory, executive function*	self-reported hypertension, self-reported high cholesterol or high blood pressure, family history of AD diagnosed before 75 years old, APOE status	noise level at night (SE = 0.36, p = 0.08) and 0.63 for Lden (SE = 0.35, p = 0.07) (impact per 1 dB)						
Irgens-Hansen et al., 2015	N = 87, Age 18–61 (mean 31 ± 9), 8% female, Norway	Measured noise exposure at work (navy personnel), ranging 67.2 to 99.1 dB(A)	the Posner cue-target paradigm *Attention*	Age, alertness, workload, noise exposure in test location, sleep the night before, use of HPD, gender, time spent in different locations, caffeine, nicotine	Differences in RT relative to < 72.6 dB(A): For 77.1–85.2 dB (A) No cue condition: 23.8 ms (95 %CI: 6.4–41.3) Valid cue: 25 (7.7–42.4) Invalid cue: 18.7 (-2.6–40.1). For > 85.2 dB(A) No cue: 24.6 (5.0–44.2) Valid cue 18.9 (-0.6–38.4) Invalid cue 12.9 (-11.0–36.8). No differences in percentage accuracy.	DH	PL	PL	DL	DL	DL
Ju et al., 2021	N = 191,054, Ages ≥ 19 years, 53.7% female, South Korea	Rated quality of noise pollution in their residential area, responses grouped into 'good' and 'bad'. Definition of noise pollution provided.	Self-reported subjective cognitive decline (SCD; confusion or memory loss that is happening more often or is getting worse) and self-reported limitations in daily activities or in their ability to work, volunteer, or participate in social life activities *Cognitive decline*	age, sex, education level, income, job classification, marital status, area of residence, body mass index, participation in a healthy lifestyle, perceived stress, depressive symptoms, and poor sleep quality	Perceived noise pollution risk of SCD: OR = 1.11; 95% CI, 1.06–1.16). SCD related functional difficulties: OR = 1.03; 95% CI, 0.88–1.21	DL	PL	PL	DH	DH	PL
Julvez et al., 2021	N = 1275 mother–child pairs, Age 6–11 (Mean	Modelled 24-hour traffic	Raven Coloured Progressive Matrices	Cohort, maternal age, maternal	None of prenatal traffic noise	DL	PL	PH	PL	DL	PH

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Table 1 (*continued*)

Author and year	Analytical sample: n, age (μ and σ unless stated otherwise), gender, location	Measurement of exposure	Measure of cognition	Confounders considered (controlled for or demonstrated unrelated)	Outcomes- most adjusted model *p < .05	Risk of bias DH: Definitely High PH: Probably High PL: Probably Low DL: Definitely Low Definitions of DH, PH, PL, DL found in supplementary materials (C)					
						Selection bias	Confounding bias	Attrition/ Exclusion bias	Exposure characterisation	Outcome characterisation	Selective reporting bias
	age 8), 45.3% female, UK France Spain Lithuania Norway Greece	noise prenatally, and at residence during childhood, categorised in dB(A): <55; 2:55–59.9; 3: 60–64.9; 4: >=65	Test [CPM], Attention Network Test [ANT], and N-Back task. *Fluid intelligence, attention, working memory*	education level, trimester of the year of child conception, child age, child sex	(Lden), or traffic noise (Lden and Lnight) at home during childhood, were significantly associated with cognition. Effects of high noise (≥65 dB (A)) relative to low (<55) ranging from −18.158 (night noise and ANT (HRT_SE), 95% CI: −45.395, 9.078) to 0.106 (prenatal traffic noise and CPM N correct responses, 95% CI: −0.844, 1.056).						
Klatte et al., 2017	N = 1090, Age 7–10 (mean 8.33 ± 0.42), 51% female, Germany	Modelled school-level aircraft noise exposure for 12 months prior to testing (also modelled home but not evaluated due to collinearity), ranged from 30 to 77 dB LAeq,07–23	Ein Leseverständnistest für Erst- bis Sechstklässler (ELFE 1–6) *Reading comprehension*	Age, gender, SES, migration background, language proficiency, number of children's books at home, nonverbal abilities, phonological representations access, phonological awareness, class SES, class migration background, class size, parental involvement, classroom insulation, road-traffic noise at school, railroad noise at school	Fully adjusted model of aircraft noise (dB) on global reading ability: standardised β: −0.327(±0.172), p = .029. A 10 dB increase in noise exposure was associated with decreases equivalent 1 month of reading development	PL	PL	PH	PL	DL	DL
Onchang, 2018	N = 786, mean age male off campus	Measured noise in on and off	Self-reported cumulative GPA	None	Off campus students had	DH	DH	PH	PL	DH	PH

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Table 1 (*continued*)

Author and year	Analytical sample: n, age (μ and σ unless stated otherwise), gender, location	Measurement of exposure	Measure of cognition	Confounders considered (controlled for or demonstrated unrelated)	Outcomes- most adjusted model *p < .05	Risk of bias		DH: Definitely High PH: Probably High PL: Probably Low DL: Definitely Low		Definitions of DH, PH, PL, DL found in supplementary materials (C)	
						Selection bias	Confounding bias	Attrition/ Exclusion bias	Exposure characterisation	Outcome characterisation	Selective reporting bias
	21.16 ± 1.44/ female off campus 20.73 ± 1.08/ male on campus 20.61 ± 1.21/ female on campus 20.51 ± 1.06, 73% female, Thailand	campus areas to compare students living in and off campus, applied noise annoyance questionnaire (International Commission on the Biological Effects of Noise). Mean $L_{eq,\ 24h}$ off-campus 64.7 ± SD 4.8, on-campus 60.3 ± 1.8.	(0–4) *Academic ability*		significantly higher noise exposure, subjective perceptions did not differ. Campus group had significantly higher GPA than outside group (mean 2.80 vs 2.83, p < .001) Noise annoyance was not consistently related to GPA (ORs from 1.049 to 1.164 but 95% CIs crossing 0). In off campus group, self-reported noise impacting reading and mental tasks was related to poor GPA (OR 2.801).						
Papanikolaou et al., 2015	N = 676, Age 9–10, 52.10% female, Greece	Measured noise at school and classified schools: Low-level noise: 55–66 dB, Medium-level noise: 67–77 dB, High-level noise: 72–80 dB	National Curriculum based test *Reading comprehension, word study, mathematical skills*	Stratify analyses by gender; argue it is a homogenous sample in terms of background	Schools with low-level noise were better at reading than medium and high level noise schools (p < .001) and better at maths than high level noise schools (p < .001). Task completion was better in low noise than high noise (X2 = 14.190, p < 0.001).	PL	PH	PL	DL	PL	PL
Tzivian et al., 2016a	N = 4050, Age 49–84 (mean 64.29 ± 7.64) 50.10% female, Germany	Modelled average address-level pollution, traffic load at major roads nearby, mean noise (Lden) and night time mean noise (Lnight) in	Verbal fluency test (number of animals named in 1 min), labyrinth test, eight word list learning (immediate rand delayed recall), clock-drawing test	Age, gender, SES, alcohol consumption, smoking status, ETS, regular physical activity, BMI, cholesterol, heart disease, diabetes, APOE	Global cognitive score significantly associated with all 6 pollutants (betas from −0.12 to −0.28, 95% CI's from −0.42;-0.15 to −0.22;-0.02). Most subtests	PL	DL	DH	PL	DL	DL

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Table 1 (*continued*)

Author and year	Analytical sample: n, age (μ and σ unless stated otherwise), gender, location	Measurement of exposure	Measure of cognition	Confounders considered (controlled for or demonstrated unrelated)	Outcomes- most adjusted model *p < .05	Risk of bias		DH: Definitely High PH: Probably High PL: Probably Low DL: Definitely Low		Definitions of DH, PH, PL, DL found in supplementary materials (C)	
						Selection bias	**Confounding bias**	**Attrition/ Exclusion bias**	**Exposure characterisation**	**Outcome characterisation**	**Selective reporting bias**
		2001–2003 (assessment 2006–2008). Mean Lden 53.74 ± SD 9.49; Mean Lnight 44.88 ± 9.17	*Global cognitive score (general cognition)*	genotypes, depression	except clock drawing test associated with air pollution. Noise and traffic load largely unrelated to cognitive performance (1/21 effects significant)						
Tzivian et al., 2016b	N = 2050, Age 49–84 (mean 64.1 ± 7.7), 50.9% female, Germany	Modelled average address level pollution, traffic load at major roads nearby, mean noise (Lden) and night time mean noise (Lnight) in 2001–2003 (assessment 2006–2008) Mean Lden 53.74 ± SD 9.49; Mean Lnight 44.88 ± 9.17	Same cognitive performance battery as above *Mild Cognitive Impairment (MCI) with or without amnesia (problems in memory domain, MCIa)*	Age, gender, SES, alcohol consumption, smoking status, ETS, regular physical activity, BMI, cholesterol, heart disease, diabetes, APOE genotypes, depression	Most exposures associated with MCI and MCIa, e.g. 1IQR increase in PM2.5 and overall MCI odds ratio 1.16 (95% CI 1.05, 1.27) and MCIa 1.22 (1.08, 1.38). A 10 dB(A) increase in LDEN and MCI OR 1.40 (1.03, 1.91) and MCIa 1.53 (1.05, 2.24). Traffic load was not associated. Noise & pollution multiexposure models attenuated the effects of each	PL	DL	PL	PL	DL	DL
Tzivian et al., 2017	N = 3885, Age 50–80 (mean 66.4 ± 7.6), 50.70% female, Germany	Pollution and noise as above, combined effects	Same cognitive performance battery as above *Global cognitive score*	Age, gender, SES, alcohol consumption, smoking status, ETS, regular physical activity, BMI, cholesterol, heart disease, diabetes, APOE genotypes, depression	Stronger associations of PM2.5, PMcoarse and PM10 on cognitive function with LDEN ≥ 60 dB (A) compared to LDEN < 60 dB (A), e.g. 1IQR PM2.5 and GCS, β = −0.48 [−0.72;-0.23] compared to β = −0.16 [−0.33; 0.01] (p intercept = 0.04). Where AP exposure was high, noise and cognition consistently	PL	DL	PL	PL	DL	DL

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Table 1 (*continued*)

Author and year	Analytical sample: n, age (μ and σ unless stated otherwise), gender, location	Measurement of exposure	Measure of cognition	Confounders considered (controlled for or demonstrated unrelated)	Outcomes- most adjusted model *p < .05	Risk of bias: Selection bias	Confounding bias	DH: Definitely High PH: Probably High PL: Probably Low DL: Definitely Low — Attrition/ Exclusion bias	Exposure characterisation	Definitions of DH, PH, PL, DL found in supplementary materials (C) — Outcome characterisation	Selective reporting bias
					associated but null or weakly positive if AP exposure was low.						
Wass et al., 2019	N = 82, Age 12 months (mean age 0.96 ± 0.01), 60.7% female, UK	Recorded noise exposure at home (daytime), computed high and low noise groups based on median split (range 30–80 dB)	Visual attention test, sustained attention test *Attention*	household income, maternal education, stressful events around birth, adverse life events since birth, parental anxiety, parental depression, parental over involvement *not related to exposure*; the number of people living at home *was associated* and not controlled for; Data were z-scored to control for individual differences	Immediately following the novel stimulus, Wilcoxon tests indicated no group differences in attention (p = .38), but at later time intervals a significant difference emerged (p = .024) suggesting greater sustained attention in the low noise group, which was replicated in the second measure of sustained attention.	PL	PH	PH	DL	DL	PL
Weuve et al., 2021	N = 5227, Age ≥ 65 years (mean age 351.9 days ± 4.6 days), 62% female, USA	Modelled residential long-term noise exposure (based on measurements, rail and traffic exposure) as an average, ranging from 51.1 to 78 dBA	The Symbol Digit Modalities Test, the East Boston Memory Test, and the Mini-Mental State Examination, Neurologist assessment *Global Cognition, Episodic Memory, perceptual speed, MCI*	Calendar time, baseline age, age at exam, sex, race, income, education, neighbourhood SES, smoking, alcohol use, and air pollution (NOx)	10-dBA increment in noise exposure corresponded to a 36% higher odds of MCI (95% CI: 1.15, 1.62). A 10-dBA noise increase associated with a 0.04 standard deviation (SD) unit lower global cognition score (95% CI –0.11 to 0.03). Driven by perceptual speed score (–0.09 SD per 10 dBA, 95% CI: –0.16 to –0.03) and not episodic memory (0.005 per	PL	DL	PH	PL	DL	DL

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Table 1 (*continued*)

Author and year	Analytical sample: n, age (μ and σ unless stated otherwise), gender, location	Measurement of exposure	Measure of cognition	Confounders considered (controlled for or demonstrated unrelated)	Outcomes- most adjusted model *p < .05	Risk of bias: Selection bias	Confounding bias	DH: Definitely High PH: Probably High PL: Probably Low DL: Definitely Low: Attrition/ Exclusion bias	Exposure characterisation	Definitions of DH, PH, PL, DL found in supplementary materials (C): Outcome characterisation	Selective reporting bias
					10 dBA; 95% CI: –0.08, 0.10).						
Yu et al., 2020	N = 1,612, Age ≥ 60 years (mean age 70, SD 6.8), 58% female, USA	Modelled day–night average (Ldn) and night-time (22:00–07:00, Leq,n) traffic noise levels at residence. Annual average levels 24 h exposure range 39 to 100 dB, and nighttime 31 to 92 dB	The Modified MMSE and delayed word recall trial (from SEVLT), *Performance reviewed by neurologists/ neuropsychologists to determine Dementia or Cognitive Impairment without Dementia (CIND)*	Baseline age, gender, years of education, occupation during most of life, smoking status, alcohol consumption status, physical activity level, NSES indicator, residential county, baseline Charlson index, baseline cognition function, and primary language, (in second analysis), NOx	24-hour noise exposure and risk of developing dementia or CIND per 12 dB increase, Hazard Ratio (HR) = 1.3 [1.0, 1.6]. Additionally Adjusted for Traffic-related NOx, slightly attenuated (HR = 1.2 [0.97, 1.6]). A corresponding paper showed this was stronger in people with metabolic dysfunction)	PH	DL	DL	PL	DL	PL
Zeydabadi et al., 2019	N = 1654, Mean age Noise group: 33.92 (7.95); Control group: 37.62 (8.13), 0% female, Iran	Measured noise exposure at work, compared workers exposed to 85dBA + and workers exposed to under 80dBA (same industry, similar tasks). Mean (±SD) of noise exposure was 92.78 ± 5.9 dBA and 74.16 ± 6.2 dBA respectively.	Visual attention test, Wechsler memory test *Attention and memory*	Age and time in job measured and reported, but nothing controlled for in group comparison analyses	All cognitive functions significantly changed after the shift in the noise group, significantly differing from the control group (high noise intensity had more impact than low)	DH	DH	PL	DL	DL	PL

Table 2
Prior literature identified by Clark & Paunovic, summary of findings and risk of bias.

Paper	Methods	Outcome	Risk of bias			DH: Definitely High PH: Probably High PL: Probably Low DL: Definitely Low		
			Selection bias	Confounding bias	Attrition/ Exclusion bias	Exposure characterisation	Outcome characterisation	Selective reporting bias
Bronzaft, 1975	Noise exposure measured in one classroom of school, comparing noisy classrooms (measured, mean 59 dBA and max 89 dBA) to quiet classrooms (unspecified). N = 161 2nd, 4th and 6th graders (14 classes).	Children on noisy side of school had poorer reading achievement (word knowledge and reading comprehension) compared to children on quiet side of school	PH	PH	PH	PH	DL	PL
Bronzaft, 1981	Same study as above. Noise measured inside (noisy but not quiet) classroom, comparing quiet and noisy side of school as well as pre and post noise-abatement measures. N = 350 (first testing), N = 605 (second testing), 2nd-6th graders	Children on noisier side of school had poorer reading achievement, but after abatement children on both sides had similar scores	PH	PH	DL	PL	DL	PL
Clark et al., 2006	Measured aircraft noise levels at home and school. Combined measured and modelled road traffic noise at school, N = 2010 9–10 year olds. Aircraft noise home Mean 50 dB, range 31–76 dB.	Increased aircraft noise at school associated with reduced reading comprehension. Aircraft noise at home correlated with reduced reading comprehension. Road traffic noise not associated.	PL	DL	PH	DL	DL	PL
Clark et al., 2012	Aircraft noise at home and school measured; road traffic noise at school from models and measurements. N = 960 9–10 year olds. Aircraft noise at school range 34–68 dBA, traffic noise at school range 37–67 dBA.	Aircraft noise at school associated with worse reading comprehension, recognition memory and conceptual recall, but not information recall or working memory. Road traffic noise not associated. Air pollution not associated, nor did it moderate the noise-cognition relationships.	PL	DL	DH	DL	DL	DL
Clark et al., 2013	Aircraft noise levels measured; road noise ascertained from measurements and models. Studied from age 9–10 (N = 1355) to age 15–16 (N = 461). Mean aircraft noise primary school 54 dB (range 34–68); Mean traffic noise primary school 51 dB (37–67). Mean aircraft noise secondary school 55 (49–68).	Reading comprehension; higher aircraft noise significantly associated with decreased reading comprehension in primary school after adjustment for confounders. However, not convincingly associated at follow-up/secondary school.	PL	DL	PH	DL	DL	DL
Cohen et al., 1973	Measured noise levels outside apartment buildings (75–84 dBA), inside hallways, and inside apartments to confirm floor level as noise exposure metric. N = 54 children (2nd-5th grade) who lived in	Children living in noisy apartments for>4 years had correlations between floor level and auditory discrimination and floor level and reading ability, and between auditory discrimination and	PH	PL	PH	PH	PL	PL

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Table 2 (*continued*)

Paper	Methods	Outcome	Risk of bias: Selection bias	Confounding bias	Attrition/ Exclusion bias	DH: Definitely High PH: Probably High PL: Probably Low DL: Definitely Low: Exposure characterisation	Outcome characterisation	Selective reporting bias
	apartment buildings of varying noise levels	reading abilities, suggesting noise exposure impaired reading through auditory discrimination.						
Cohen et al., 1981a and 1981b	Measured aircraft noise inside classroom, comparing noisy, noise-abated and quiet classrooms. N = 163 (longitudinal) and N = 262 (cross-sectional) third and fourth graders. Mean peak noise level noisy classrooms 79 db (A); abated classrooms 63db(A); quiet 57 db(A).	Cross-sectional; noisy classrooms children more often failed puzzle test. Longitudinal; Children from noisy schools were less distractible but more often failed puzzles and took longer to do them. Auditory discrimination and reading achievement unrelated.	PL	PL	PH	DL	DL	PL
Eagan et al., 2004 and Zusman, 2007 (FICAN report)	Modelled indoor aircraft noise, before and after an airport closure or school sound insulation. N = unspecified 6–18 year olds from 35 schools	Noise reduction associated with reduced failure rate in high school compulsory verbal and math/science tests, but not younger pupils, and an increase in top-score rates of children with disabilities.	PH	DL	PH	PL	PL	DL
–	Flight contours modelled aircraft noise around schools, N = 116 5–7 year olds from two demographically similar schools	Chronic aircraft noise correlated with worse reading scores and speech perception, with speech perception mediating the relationship of noise exposure and poor reading skills	PH	PH	PL	PL	PL	PL
Green et al., 1982	Modelled aircraft noise contours around schools, assigned noise scores to 362 schools, N = unspecified 2nd-6th graders	Aircraft noise associated with % pupils below grade reading level (nationally standardised tests).	PL	PL	PL	PL	DL	PL
Haines et al., 2001a	Aircraft noise modelled around schools and measured inside classrooms; N = 340 8–11 year olds studied, and N = 275 again a year later. Grouped into noisy (16hr Leq > 63 dBA) and quiet (<57dBA) schools. N = 451 8–11 year olds.	At follow-up children from high-aircraft noise-impacted schools had worse reading comprehension and sustained attention than children from low-aircraft noise-impact schools.	DL	PL	PH	DL	DL	DL
Haines et al., 2001b	Aircraft noise levels modelled around 20 schools, Noisy classrooms: 16hr Leq > 66dBA, quiet: <57 dBA	High noise exposed children had poorer performance on difficult items of the Suffolk reading comprehension scale, but did not significantly differ on total reading comprehension score, sustained attention, immediate recall, delayed recall, delayed recognition, or backward digit span	DL	PL	PH	PL	DL	DL

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Table 2 (*continued*)

Paper	Methods	Outcome	Risk of bias			DH: Definitely High PH: Probably High PL: Probably Low DL: Definitely Low		
			Selection bias	Confounding bias	Attrition/ Exclusion bias	Exposure characterisation	Outcome characterisation	Selective reporting bias
Haines et al., 2001c	Aircraft noise modelled around 8 schools, and measured indoors, for N = 340 8–11 year olds. Noisy classrooms:16hr Leq > 66dBA, quiet: <57 dBA	High noise exposed children had poorer performance on reading comprehension and long-term memory recognition (in a subsample) than low noise exposed children. Aircraft noise had no significant effect on long-term memory recall performance or short-term memory and recognition.	DL	PL	PH	PL	DL	DL
Haines et al., 2002	Aircraft noise modelled around 123 schools, N = 10957–11163 (depending on test) 11 year olds. Low noise exposure Leq (16 hr) =<57 dBA; Moderate noise exposure = 57 > 63 dBA; high noise exposure = 63 > 72 dBA.	Increased aircraft noise contour band associated with decreased SAT Key Stage 2 standardised reading and maths test performance but not after controlling associated with English (spelling, handwriting, creative writing for free school meals. Not) or science	DL	PL	DL	PL	DL	DL
Hygge et al., 2002	Measured aircraft noise levels around schools before and after relocation of an airport. N = 326 8–12 year olds. Range of mean 24 hr Leq: 53-68dBA.	Newly exposed; decreased correct answers on long-term memory test, impairment of speech perception. After relocation of old airport, formerly exposed showed; decreased number of errors on reading test, increased correct answers on short-term memory test, improved speech perception. More exposed group were slower in attentional task at time 2 (after relocation) but not 1 or 3, and after the new airport opened the newly exposed group were slower than non-exposed group.	PL	PH	PL	DL	DL	PL
Klatte et al., 2014 (report, results published in English in an academic journal in 2017, see Klatte et al., 2017)	Aircraft noise contours at school and home around airport, N = 1090 ~ 8 year olds. $LA_{eq,07\text{-}23}$ ranged from 30 to 77 dB	Increased aircraft noise associated with reduced reading comprehension (equivalent to a month's reading delay). Similar for subscales (word and text comprehension) and aircraft noise at home. Language functions (speech perception, auditory thinking, phonological short-term memory, phonological awareness, episodic	PL	PL	PH	PL	DL	DL

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Table 2 (*continued*)

Paper	Methods	Outcome	Risk of bias			DH: Definitely High PH: Probably High PL: Probably Low DL: Definitely Low		
			Selection bias	Confounding bias	Attrition/ Exclusion bias	Exposure characterisation	Outcome characterisation	Selective reporting bias
		memory test) unrelated.						
Lercher et al., 2003	Rail and road noise either modelled or measured (unspecified) for N = 123 aged 9–10, comparing noisy and quiet neighbourhoods (62 dBA Ldn and 46.1 dBA Ldn)	Children from high noise group had poorer results on explicit and incidental memory tests, but not attention (visual search task) or motivation (solving insolvable and solvable puzzle).	PL	DH	PL	PH	PL	PL
Lukas et al., 1981 (report)	Noise levels measured outside schools, in community and inside classrooms, comparing noisy and quiet schools, N = 1826 3rd and 6th graders	Pupils had poorer reading and mathematics achievement compared to those from quieter schools (e.g. 6th graders were 0.7 years behind in reading).	PL	DL	DL	DL	DL	PL
Matheson et al., 2010	Aircraft noise measured or modelled at home and school. Road traffic noise combined from measurements and models. N = 2844 9–13 year olds from 89 schools. Aircraft noise at school ranged from 32 to 77 dB $L_{Aeq\ 16\ h}$ and road traffic noise at school ranged from 31 to 71 dB $L_{Aeq\ 16\ h}$.	Increased road traffic noise associated with increased information and conceptual recall but not recognition or prospective memory. Aircraft noise associated with decreased recognition memory, but not related to prospective memory, information recall, or conceptual recall.	PL	DL	PL	PL	DL	DL
Matsui et al., 2004	Aircraft noise at home and at school modelled, all with high exposure at school to assess impact of varying home exposure levels. N = 163 8–9 year olds. 10 schools high-aircraft noise areas (16-hr outdoor LAeq > 63 dB) and 10 schools were in low-aircraft noise-impact urban areas (16-hr outdoor LAeq < 57 dB).	Noise levels at home associated with poorer immediate and delayed recall, but not delayed recognition memory, sustained attention or reading comprehension.	PL	PL	DH	PL	DL	DL
Pujol et al., 2014	Modelled noise exposure outside homes (mostly traffic noise) for N = 587 8–9 year olds. Average LAeq,day at school 51.5 dB (SD = 4.5 dB; range = 38 – 58 dB). Outdoor Lden home 56.4 dB (SD = 4.4 dB; range = 44–69 dB).	Noise exposure at home was not negatively associated with scores in French and maths after adjustment for confounders. Noise at school associated with worse scores in French and maths (after adjustment for confounders).	DL	PL	PH	PL	DL	DL
Sanz et al., 1993	Road traffic noise measured inside and outside classrooms for N = 136 6–11 year olds. Quiet schools Outdoor Leq range 47.5–69.1 dBA, Loud schools 58 5–76 6 d BA.	Children from high noise school had poorer result on 'text test' in grade 3 (crossing out letters from a text, attention), no differences on face test (difference perception test).	PL	DH	PH	DL	PL	DL
Seabi et al., 2012	Measured noise levels outside schools in	High aircraft noise groups had lower	PL	PL	PL	DL	DL	PL

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Table 2 (*continued*)

Paper	Methods	Outcome	Risk of bias			DH: Definitely High PH: Probably High PL: Probably Low DL: Definitely Low		
			Selection bias	Confounding bias	Attrition/ Exclusion bias	Exposure characterisation	Outcome characterisation	Selective reporting bias
	mornings, high noise (near flight path, 16hr outdoor Leq 63.5 to 69.9) and low noise (50.5–57.9 Leq) schools compared, N = 693 9–14 year olds.	reading comprehension than low noise groups; the effect was stronger for those whose primary home language was not English						
Seabi et al., 2015	Measured noise levels outside schools before (2009) and after (2010–2011) relocation of an airport. 9–15 year olds measured at three timepoints (Ns = 732; 650; 178). Leq reduced from range 63.5–69.9, to average of 55.2 dB.	Reading comprehension significantly differed in 2009 between high and low exposed groups; no significant differences between high and low noise groups in 2010 or 2011 (adjusted) and no interaction effect of exposure and time on reading comprehension, i.e. removing aircraft noise did not improve reading but prior chronic exposure did not worsen it	PL	PL	DH	DL	DL	PL
Sharp et al., 2014 (report)	Modelled aircraft noise levels at school, N = unspecified 3rd, 4th, 5th graders from 6198 schools, evaluating effects of noise exposure and (for a subsample) sound insulation installation. Exterior Leq mean 54.2 dB, SD 5.2	Aircraft noise associated with decreased school state ranking, based on school average test scores in reading and mathematics. Subsample (119 schools) had sound insulation installed which removed this effect of aircraft noise on ranking.	DL	PL	PL	PL	PL	PL
Shield and Dockrell (2008)	Noise levels measured inside and outside schools, N = unspecified 7–11 year olds (142 schools external noise, 16 schools internal noise). External Leq range49 to 75 dB (A).	External noise levels associated with average test scores of KS1 and KS2 in suburban schools but not urban schools, poorer mathematics and science in suburban schools, and poorer KS1 and KS2 English in urban schools. Internal noise associated with poorer KS1 maths and KS2 English.	PL	PH	PH	DL	DL	PL
Stansfeld et al., 2005	Measured Aircraft noise levels at school and home, road traffic noise at school modelled in combination with measurements; N = 1938–2014 (depending on task) 9–10 year olds. Leq ranged from 30 to 70 dB.	Increased school aircraft noise associated with decreased reading comprehension and recognition memory; Road traffic noise at schools associated with better cued information and conceptual recall; noise not associated with prospective memory, working memory, sustained attention	PL	DL	PH	DL	DL	DL
			PL	DL	PH	PL	DL	DL

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Table 2 (*continued*)

Paper	Methods	Outcome	Risk of bias: Selection bias	Confounding bias	Attrition/ Exclusion bias	DH: Definitely High PH: Probably High PL: Probably Low DL: Definitely Low: Exposure characterisation	Outcome characterisation	Selective reporting bias
Stansfeld et al., 2010	Measured and modelled aircraft noise levels around school and home, N = 326 (Munich) and N = 842 (RANCH). Mean daytime aircraft noise 53 dBA, mean night-time aircraft noise 43 dBA	Munich: no association between night-time aircraft noise and reading or long-term memory. RANCH: night-time noise at home associated with decreased reading and recognition memory, but not after adjusting for daytime aircraft noise at school (highly correlated). Neither night-time or daytime exposure associated with recall memory, information recall, attention, working memory						
Van Kempen et al., 2010	Aircraft and road traffic noise modelled for home and school addresses, N = 553 9–11 year olds from 24 schools. School $L_{Aeq,\ 7\text{-}23hr}$ 36–63 dB(A), Home Leq range 34–63 dB(A)	Aircraft noise and traffic noise at school associated with more errors on Switching Attention Task (SAT), but not with other tests; simple reaction, mixed-eye-coordination, symbol-digit substitution, digit memory, reading comprehension, prospective memory, episodic memory, working memory, sustained attention	PL	DL	PH	PL	DL	PL
Van Kempen et al., 2012	Aircraft noise and road noise at home and school modelled for N = 485 children aged 9–11 in 24 schools. Range 28–67 dB (A).	Aircraft and road noise at school associated with errors on SAT test even after adjustment for NO2 and confounders, but not with other tests (NO2 at school associated with digit memory span test); home exposures not associated. Combined No2 and road noise at home related to reaction times in simple reaction time test (SRTT) and errors in SAT (children living in areas with high levels of road traffic noise had a shorter reaction time/more errors as NO2 increased)	PL	DL	PH	PL	DL	DL

3.2.6. Global cognition, perceptual speed and executive function

Weuve and colleagues (2021) also observed a non-significant trend effect of residential noise and global cognition in their sample, which was driven by its perceptual speed component (and not its episodic memory component). However, Gotsens et al. did not observe a relationship between general cognition and residential noise, however they did observe a relationship between executive function and residential noise. The quality of evidence for associations between residential noise and general cognition, perceptual speed and executive function were low, low, and very low respectively.

Table 3
GRADE assessments of certainty of evidence.

Outcome	Exposure	Papers	Health effect (on cognition)	Initial rating	Downgrade?	Upgrade?	Confidence in body of evidence
Criteria:				**Moderate:** exposure prior to outcome (longitudinal), individual outcome data, comparison used **Low:** 2/3 'Moderate' features **Very Low:** 0–1/3 'Moderate features' **(High:** No studies used a controlled exposure therefore no studies have an initial 'High' rating)	**Possible Reasons**: Inconsistency, imprecision, Risk of Bias concerns, indirectness, publication bias	**Possible reasons:** All plausible confounders or other biases increase confidence in the observed effect, large or very large effect observed, dose–response gradient	**Low, Very Low, Moderate, or High**
Children and adolescents							
Academic ability /standardised tests	Traffic noise N = 4	Papanikolaou et al., 2015; Lukas et al., 1981; Pujol et al., 2014; Shield and Dockrell, 2008	All literature supports	Low Reason: Individual outcome data, comparison group used, but cross-sectional	No	No	Low
	Aircraft noise N = 7	Eagan et al., 2004/ Zusman, 2007; Green et al., 1982; Sharp et al., 2014; Cohen et al., 1981a; Cohen et al., 1981b; Haines et al., 2002	Most literature supports	Very low Reason: Comparison used, but mostly non-individual data and largely cross-sectional designs	No	No	Very low
Attention	Aircraft noise N = 10	Cohen et al., 1981a; Cohen et al., 1981b; Haines et al., 2001a; Haines et al., 2001b; Hygge et al., 2002; Matsui et al., 2004; Stansfeld et al., 2010; Stansfeld et al., 2005; Van Kempen et al., 2012; Van Kempen et al., 2010.	Literature slightly supports	Moderate Reason: Individual outcome data, comparison used, several longitudinal studies	Moderate -> low Reason: inconsistency	No	Low
	Traffic noise N = 6	Cohen et al., 1973, Sanz et al., 1993, Stansfeld et al., 2005, Van Kempen et al., 2012, Van Kempen et al., 2010, Julvez et al., 2021	Equal mix of supportive and unsupportive literature	Low Reason: Individual outcome data, comparison used, but largely cross-sectional	Low -> Very low Reason: inconsistency	No	Very Low
	Rail noise N = 1	Lercher et al., 2003	Not supportive	Low Reason: Individual outcome data, comparison used, but largely cross-sectional	Low -> Very low Reason: Risk of Bias (RoB) concerns	No	Very Low
	Home noise N = 1	Wass et al., 2019	Supportive	Low Reason: Individual outcome data,	Low -> Very low	No	Very Low

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Table 3 (*continued*)

Outcome	Exposure	Papers	Health effect (on cognition)	Initial rating	Downgrade?	Upgrade?	Confidence in body of evidence
				comparison used, but largely cross-sectional	Reason: Risk of Bias (RoB) concerns		
Executive function	Aircraft noise N = 9	Clark et al., 2012; Haines et al., 2001a; Haines et al., 2001b; Klatte et al., 2014; Matheson et al., 2010; Stansfeld et al., 2010; Stansfeld et al., 2005; Van Kempen et al., 2012; Van Kempen et al., 2010	All unsupportive	Moderate Reason: Individual outcome data, comparison used, several longitudinal studies	No	No	Moderate
	Traffic noise N = 6	Clark et al., 2012, Matheson et al., 2010, Stansfeld et al., 2005, Van Kempen et al., 2012, Van Kempen et al., 2010, Julvez et al., 2021	All unsupportive	Low Reason: Individual outcome data, comparison used, but largely cross-sectional	No	No	Low
Fluid intelligence/IQ	Traffic noise N = 1	Julvez et al., 2021	Unsupportive	Moderate Reason: Individual outcome data, comparison used, several longitudinal studies	Moderate -> low Reason: Risk of Bias (RoB) concerns	No	Low
Reading and language skills	Aircraft N = 19	Cohen et al., 1981a, 1981b; Clark et al., 2012; Clark et al., 2013; Clark et al., 2006; Green et al., 1982; Haines et al., 2001a; Haines et al., 2001b; Haines et al., 2001c; Hygge et al., 2002; Klatte et al., 2014; Klatte et al., 2017; Matsui et al., 2004; Seabi et al., 2012; Seabi et al., 2015; Stansfeld et al., 2010; Stansfeld et al., 2005; Haines et al., 2002 *Includes *meta*-analytic effects in Figs. 2 and 3.	Mostly supportive	Moderate Reason: Individual outcome data, comparison used, several longitudinal studies	Moderate -> low Reason: imprecision	Low -> Moderate Reason: dose–response	Moderate
	Traffic N = 4	Papanikolaou et al., 2015, Clark et al., 2006, Clark et al., 2012, Stansfeld et al., 2005	Mostly unsupportive	Low Reason: Individual outcome data, comparison used, but all cross-sectional	No	No	Low
	Rail N = 2	Bronzaft, 1975; Bronzaft, 1981	Supportive	Very low Reason: Individual outcome data, but no comparison (group or continuous exposure) used, and cross-sectional	No	No	Very Low
	Apartment N = 1	Cohen et al., 1973	Supportive	Low Reason: Individual outcome data, comparison used, but cross-sectional	Low -> very low Reason: RoB concerns	No	Very Low
Memory and learning	Aircraft N = 12	Clark et al., 2012; Haines et al., 2001b; Haines et al., 2001c; Hygge et al., 2002; Klatte et al., 2014; Lercher et al., 2003;	Mostly supportive	Moderate Reason: Individual outcome data,	Moderate -> Low Reason: inconsistency	No	Low

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Table 3 (*continued*)

Outcome	Exposure	Papers	Health effect (on cognition)	Initial rating	Downgrade?	Upgrade?	Confidence in body of evidence
		Matheson et al., 2010; Matsui et al., 2004; Stansfeld et al., 2010; Stansfeld et al., 2005; Van Kempen et al., 2012; Van Kempen et al., 2010		comparison used, several longitudinal studies			
	Traffic noise N = 5	Clark et al., 2012; Matheson et al., 2010; Stansfeld et al., 2005; Van Kempen et al., 2012; Van Kempen et al., 2010	Unsupportive (and two showed improvements in cognition)	Low Reason: Individual outcome data, comparison used, but all cross-sectional	Low -> very low Reason: inconsistency	No	Very low
	Rail N = 1	Lercher et al., 2003	Not supportive	Low Reason: Individual outcome data, comparison used, but cross-sectional	Low -> Very low Reason: Risk of Bias (RoB) concerns	No	Very Low
Adults							
Academic ability	Residential noise (multisource) N = 1	Onchang, 2018	Unclear	Very low Reason: Individual outcome data, comparison used, but cross-sectional	Low -> Very Low Reason: indirectness, RoB	No	Very Low
Maths and Literacy	Traffic noise N = 1	Gao et al., 2021	Supportive	Moderate Reason: Individual outcome data, comparison used, longitudinal study	Moderate -> Low Reason: RoB	No	Low
Memory	Workplace and residential noise (multisource) N = 3	Zeydabadi et al., 2019, Weuve et al., 2021	2/3 unsupportive	Low Reason: Individual outcome data, comparison used, but cross-sectional	Low -> Very Low Reason: ROB/inconsistency	No	Very low
Attention	Workplace noise N = 2	Irgens-Hansen et al., 2015, Zeydabadi et al., 2019	Supportive	Low Reason: Individual outcome data, comparison used, but both cross-sectional	Low -> Very Low Reason: ROB	No	Very low
Cognitive impairment	Traffic noise N = 7	Fuks et al., 2019, Tzivian et al., 2016a, Tzivian et al., 2016b, Tzivian et al., 2017, Ju et al., 2021, Weuve et al., 2021, Yu et al., 2020 *includes *meta*-analytic effect in Fig. 4.	Supportive	Moderate Reason: Individual outcome data, comparison used, several longitudinal studies	No	Moderate -> High Reason: Large effect (*meta*-analysis OR 1.40)	High, possible synergistic effect with pollution
Global cognition	Residential noise (multisource) N = 2	Weuve et al., 2021	1/2 supportive	Moderate Reason: Individual outcome data, comparison used, includes longitudinal study	Moderate -> Low Reason: Inconsistency, RoB concerns	No	Low
Perceptual speed	Residential noise (multisource) N = 1	Weuve et al., 2021	Supportive	Moderate Reason: Individual outcome data,	Moderate-> Low Reason: inconsistency	No	Low

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Table 3 (*continued*)

Outcome	Exposure	Papers	Health effect (on cognition)	Initial rating	Downgrade?	Upgrade?	Confidence in body of evidence
				comparison used, longitudinal study	(consistency can't be judged from a single study, and inconsistent with Gotsens in overarching global cognition outcome)		
Executive function	Residential noise (multisource) N = 1	–	Supportive	Low Reason: Individual outcome data, comparison used, but cross-sectional	Low -> Very Low Reason: RoB concerns	No	Very Low

3.3. *Overall trends across cognitive outcomes*

Fig. 5 summarises the direction and strength of the evidence for different outcomes. 2 areas have not been studied ('n/a'), and Table 3 explicates the quality of overall evidence judgements made for each outcome and exposure, including the references of studies each encompasses.

In order to evaluate publication bias and summarise the general trend of effects (though limited in meaning given such heterogeneous outcomes), funnel plots were produced of the different statistical estimate types which could be extracted from the literature across cognitive outcomes (Figs. 6a, 2b, and 2c). The most common statistic provided was a beta coefficient, usually reflecting the change in cognitive score for a 1 dB increase in environmental noise exposure, which showed a pattern inconsistent with publication bias but consistent with only a very subtle effect overall (Fig. 6a, β −0.0031 [95% CI: −0.0062; 0.0000]). The plotted estimates of Odds Ratios for high (>50–66 dB) relative to low (<50–63 dB) noise exposure upon cognitive deficit (Fig. 6b, 1.22 [95% CI: 0.99; 1.45]) and mean differences in scores on cognitive tasks between exposed (59–85.2 dB) and non-exposed (47–72.6 dB) groups (Fig. 6c, exposed 1.6270 points lower [95% CI: 3.7262; 21.5958]) showed trends supportive of a general relationship but also indicative of possible publication bias.

4. Discussion

4.1. *Summary*

The study findings had a high degree of variation but tended to indicate some associations between the different exposures and cognitive outcomes. There was high quality evidence that residential noise is associated with cognitive impairment in 45 + year-olds, moderate quality evidence that noise exposure (especially aircraft noise) was associated with reading and related abilities in children, and moderate quality evidence that executive function was not associated with aircraft noise in children, but evidence for other noise associations is low or very low quality (poor quality research or insufficiently investigated), and we would reiterate Clark & Paunovic's message (2018a) that more robust studies are still required. This is particularly the case for studies of general cognition and IQ, processing speed/reaction time, psychomotor abilities, and language/reading abilities in adults. Further, the literature on young-to-middle-aged adult populations was scarce and inconclusive for all outcomes. Children and teenagers (up to 18) were categorised together, but the majority of the children and adolescent's literature evaluated relationships in childhood and early adolescence. 2 studies in this review included young people aged 15–18, when the brain is still very much developing, so this late adolescence and young adulthood period require more attention and there is not conclusive evidence as to this age group either. Clark et al delineated by noise sources (kinds of transport) so we followed this structure in GRADE assessments incorporating newer literature, when the research design was specific to type of transport noise source. However, some new studies evaluated total noise, source of noise other than transport noise, or combined noise from several sources, so these associations with cognition were evaluated as applicable to the literature. Its plausible that some mechanisms of impact are source-specific than others, e.g. if airplane and helicopter noise were more annoying than other sources (Miller et al., 2021) but general physiological stress responses were mainly affected by volume (Nilsson, 2018).

As well as supporting positive health outcomes (Brown and Van Kamp, 2017), policies and interventions that reduce human noise exposure should therefore prevent noise-related cognitive deficits in children and adults. Several studies observed improvements in reading after noise abatement procedures took place in schools (Cohen et al., 1981b, Eagan et al., 2004, Seabi et al., 2015) which provides a clear mandate for better noise insulation in schools, particularly in urban areas or areas proximal to transport and industry. Families and contractors should therefore be supported to install materials in homes that both provide sound and heat insulation. Policy makers should incentivise transport and industry business to implement noise mitigation techniques, such as the avoidance of residential and school areas and limiting night time operations.

Exposure of the world's population to noise is increasing in prevalence and severity, and if this negatively impacts cognitive abilities, it has wider implications for socioeconomic conditions, health outcomes, and overall wellbeing in a global context (Batty et al., 2007, Firkowska-Mankiewicz, 2011). Therefore, these results suggest that policies mitigating such exposures could have a range of benefits for human health and wellbeing beyond cognitive performance.

However, the quality of evidence was generally low. The most common reasons for initially rating evidence as low was cross-sectional design (as the time sequence of exposure and outcome is not ascertain), and downgrading occurred most frequently, for inconsistency between study findings and risk of bias concerns. Risk of bias concerns were mostly due to sample attrition or exclusion (24 studies), inadequate controlling for confounding (10), and representative population sampling (9). Usually the method of exposure and outcome assessment were considered reasonable and did not often lead to downgrading. Selective reporting did not emerge as a major concern; however some funnel plots were suggestive of publication bias. Therefore, it is possible that our conclusions do not reflect the entirety of the true evidence base. However, the majority of studies observed effects including studies without risk of bias concerns, so we would tentatively conclude that noise is associated with some aspects of cognition, and that the inconsistencies are attributable to complexities in the phenomena (i.e. the effect depending on the specific context and population) and the heterogeneities in the studies (e.g. different methods and tools being used, different confounders being adjusted for, different exposure windows).

4.2. Future research

Adults and teenagers were neglected in the literature, despite the fact that there are plausible mechanisms of noise exposure on cognition which apply in these age groups; for example, stress and sleep could impact cognition in all age groups (Lupien et al., 2009, Wilckens et al., 2014), especially in teenagers who are still cognitively developing and are considered especially vulnerable to psychological risk factors for this reason.

Research should investigate the modifying circumstances further, e.g. sociodemographics, which may help to explain differential estimates between studies, age-groups, and populations. There were far more studies from the USA and Europe, than Asia, Central and South America, Africa or Australasia. The effect of noise on cognition may not be homogenous across countries (as they could be modified by sociocultural context, air pollution levels, temperature, age of population, nature of noise, times when exposure is highest, etc.) and so more research is needed in these understudied regions. Longitudinal studies comparing multiple exposure windows, and inter-country or inter-age studies, would also be valuable for clarifying how the noise-cognition relationships present in time and space.

Future research should more clearly disentangle the impacts of noise from air pollution; noise and air pollution covary, presenting the risk of residual confounding of one to the other. Four papers from two studies (Clark et al., 2012, Tzivian et al., 2016b, Tzivian et al., 2016b; Van Kempen et al., 2012) controlled for air pollution, with Clark et al. (2012) observing no evidence of confounding but Tzivian et al. (2016a, 2016b) observing an attenuation of noise's effect when controlling for air pollution, and Van Kempen et al. (2012) observing a relationship between school transportation noise and errors on the switching attention test after adjusting for NO_2, as well as observing effect modification where children in high noise areas were more vulnerable to the effects of pollution on attention and reaction time. Another study (Tzivian et al., 2017) also looked at effect modification by stratifying the sample into groups of high/low exposure, finding that the relationship between air pollution and general cognition was stronger when noise exposure was high, and that noise was only associated with general cognition in the context of high air pollution exposure. Future research should also further consider the roles of different exposure windows (night, day, long-term, recent) and locations (comparing home, school, work, etc.).

Some research looked at mediation by potential cognitive mechanisms (distractibility, speech perception, attention, annoyance) but none looked at mediation by other factors such as biomarkers or mental health. Studies investigating observational associations between noise and cognition should combine this with mechanistic investigations in the same population- measuring indicators of response (e.g. cortisol, changes in patterns of activity or structure of the brain, questionnaire data on mental health or sleep quality) to build up the evidence that the plausible mechanisms are responsible and to enhance possible causal inference.

There is a need for further good quality noise research, especially in adults and teenagers. However, there should be a standardisation of methods used in this field, where researchers seek to apply the same methods of exposure specification and resolution, outcome assessment, and statistical analyses as past or concurrent research and thereby enable direct comparison of findings. Often researchers look for a unique angle, but scientifically this has led to many similar studies which are not directly comparable, precluding clear conclusions and precise estimation of combined effects. This is likely to have contributed to the observed heterogeneities in findings. Studies would most advance the field by either evaluating an entirely new subject area or by replicating methodology. Existing cohort studies and emerging projects should apply an integrated global approach, and the authors welcome initiatives which establish agreed core metrics, such as that by the International Alliance of Mental Health Research Funders for aggregating data related to mental health.

To align with prior literature we recommend the 24 h A-weighted mean day-evening-night noise level (Lden) to indicate residential exposure (Lden), mean day-time noise levels (Lday) for school/work exposure, and mean Lnight for night-time noise, all in decibels, as metrics of noise exposure. As a cognitive battery for adults, we recommend the CERAD-plus be applied as it contains several widely used and validated sub-tests to measure general cognition, verbal fluency, episodic memory, constructional praxis, executive function, orientation, and cognitive impairment (Fillenbaum et al., 2008). For children, the Suffolk reading scale has been most widely used to measure reading and the attention network test (particularly the HRT-SE metric) has been widely used for attention. The digit symbol substation test (DSST) has been used across ages to measure processing speed, as has the forward and backward digit span task to index short term and working memory respectively. Some of these tasks cannot be used with non-English speakers and equivalents should be used in this case. In line with prior research we recommend associations are estimated using multiple linear regression models, adjusting for covariates, to produce beta coefficients (impact per dB(A) of continuous exposure) or Odds Ratios (ORs) for high relative to low levels of exposure; Lden $\geq$ 55 dB relative to $<$ 55, Lnight $\geq$ 45 dB relative to $<$ 45 dB (following World Health Organization Environmental Noise Guidelines for the European region, 2018). Whilst the relationship between noise and cognition is not necessarily linear (perhaps exhibiting a threshold, stronger effects at higher levels, or a ceiling effect) it is recommended authors present both linear and alternative associations at the same time if they intend to explore this possibility to allow for comparison with prior findings.

4.3. Strengths and limitations

This review has several strengths, it is thorough and comprehensive; we believe it encapsulates all literature on the relationships between environmental noise exposure and general population (non-pathological) cognition, across the lifespan, up to September 2019. At least two

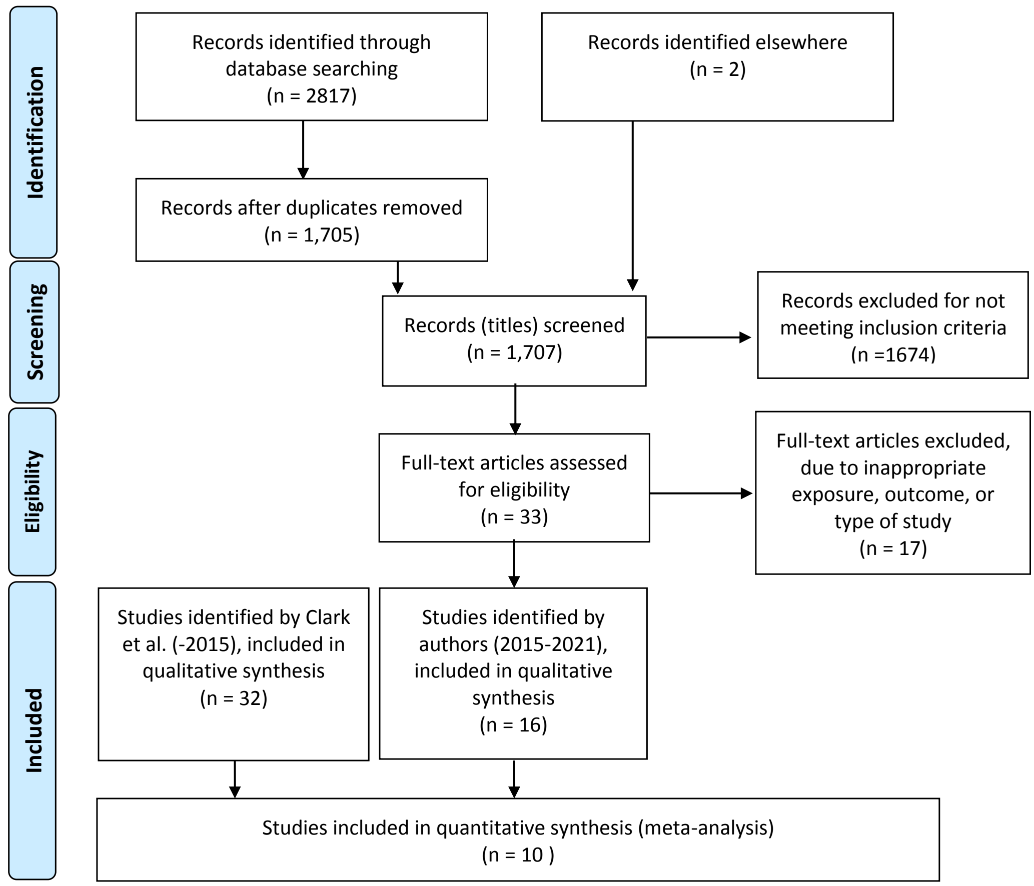

Fig. 1. PRISMA diagram of search results. *From:* Moher D, Liberati A, Tetzlaff J, Altman DG. The PRISMA Group (2009). *P*referred *R*eporting *I*tems for *S*ystematic Reviews and *M*eta- *A*nalyses: The PRISMA Statement. PLoS Med 6(7): e1000097. https://doi.org/10.1371/journal.pmed1000097.

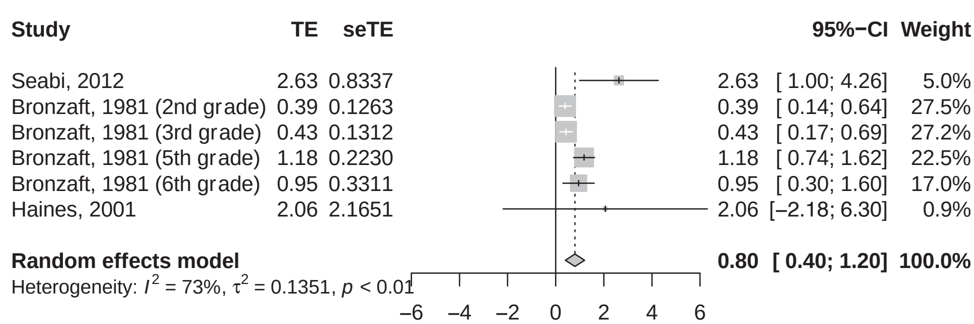

Fig. 2. The pooled mean difference in reading comprehension scores between children in high noise (average Leq 59–69.9dBA, Max Leq 89–96.5) and low noise exposed (average Leq 54.4–57 dBA, Max Leq 73.2–74.3) classrooms (TE = mean reading score of quiet classrooms – mean reading score of noisy classrooms, seTE = pooled standard error).

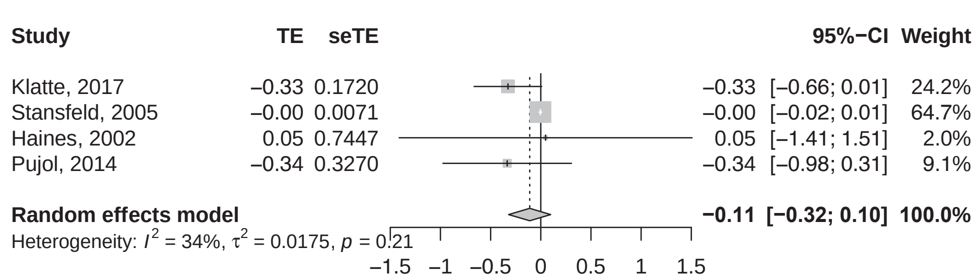

Fig. 3. The pooled beta coefficients reflecting the association between environmental noise (impact of 1 dB increase, from mixed transport sources) and reading and language abilities (TE = beta coefficient (β), seTE = β standard error).

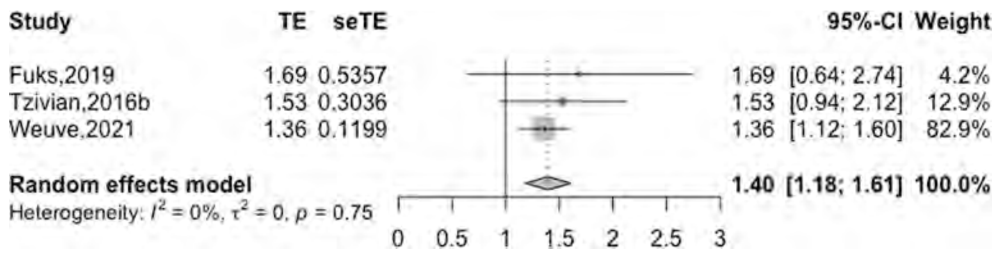

Fig. 4. The Odds Ratio (OR) of cognitive impairment in 45 + year olds exposed to higher noise (10 A-weighted decibel [dB(A)] increase or ≥ 50 dB(A)) relative to lower noise (<50 dB(A) or 10 dB(A) less). (TE = OR of cognitive impairment with higher exposure relative to 1 as Odds of cognitive impairment with lesser exposure, seTE = OR standard error).

researchers completed every stage of paper selection and extracted all review details, and risk of bias and quality of evidence was assessed with transparent, replicable and customary methodology. Possibly due to the variability in how these subject matters have been studied, this was the first *meta*-analysis on the subject. That said, results are not conclusive, because there is so much evidence that could not be quantitatively synthesised and much evidence had to be downgraded.

Some shortcomings to this research should be noted. First of all, the body of literature up to 2015 was identified by a prior review (Clark & Paunovic 2018). We did assess the quality of this prior review, but if it did not capture all of the literature this will be reflected in our synthesis of the literature. Secondly, there is always the possibility, due to systematic or human error, that relevant studies are missed, although our methodology was systematic and customary. Further, the risk of bias assessments, qualitative syntheses and GRADE evaluations were based on a partially computable method (e.g. specific design features, the size of the literature and the proportion of it that was supportive or unsupportive,) however there is still room for some subjectivity in the interpretation of the collective evidence in its various combinations- therefore we would recommend that, for studies of particular interest or relevance, researchers read the relevant table entries as well as the qualitative syntheses. Further, our *meta*-analyses cut across multiple outcome metrics, which is not ideal as it only demonstrates the trends of effects rather than precisely estimating the exposure–response relationship. If future research is standardised to align with other research, there is no a priori reason *meta*-analyses cannot be employed in future to refine our understanding of how these exposures affect cognition. Additionally, the reviewers scanning the title results selected only titles in English, and one full-text was excluded on the basis of language (Levain et al., 2015). Although the findings of this study were, we believe, reported elsewhere in English (Pujol et al., 2014) and reviewed by Clark & Paunovic (2018), it is possible relevant evidence was excluded on the basis of language. Finally, to focus on general population cognition, to be aligned with Clark & Paunovic (2018), and in consideration of the existing reviews on mental health outcomes, this review excluded clinical outcomes (as symptom schedules or diagnoses) even if they have a cognitive component (e.g. ADHD, dementia, depression). This was to avoid extending the review from cognitive to medical, emotional, behavioural, and social outcomes, however it is appreciated that there is a real life continuity (e.g. between cognitive impairment and dementia in old age, between ADHD's behavioural symptoms and measured attention) which may have left out relevant evidence for the question of cognition.

4.4. Concluding comments

This review is supportive of a general association between environmental noise pollution and cognition, in children and older adults, but adolescence and young adulthood have not been sufficiently investigated. Specifically, the evidence was strongest for cognitive impairment, and reading and language skills being related to noise exposure, and against an effect of executive function. To understand the details of these relationships, for example at which level of exposure specific outcomes are impacted and to what extent, the main mechanisms, and the contextual moderating factors, more research is required. In particular, studies should either advance the field in neglected areas or seek to systematically align with previous research to allow for more precise quantitative synthesis.

	Children	Adults
Academic ability	✓	✓
Attention	✓	✓
Memory and learning	✓	×
Executive function	×	✓
Reading and language	✓	✓
Fluid intelligence and general cognition	✓	50/50
Cognitive impairment	n/a	✓
Perceptual speed	n/a	✓

Associated in literature: ✓
Not associated in literature: ×
High Quality evidence
Moderate Quality evidence
Low Quality evidence
Very low quality evidence

Fig. 5. Summary of direction (supportive or not supportive) and rating of confidence (high, moderate, low, very low) in evidence for associations between environmental noise and cognitive outcomes.

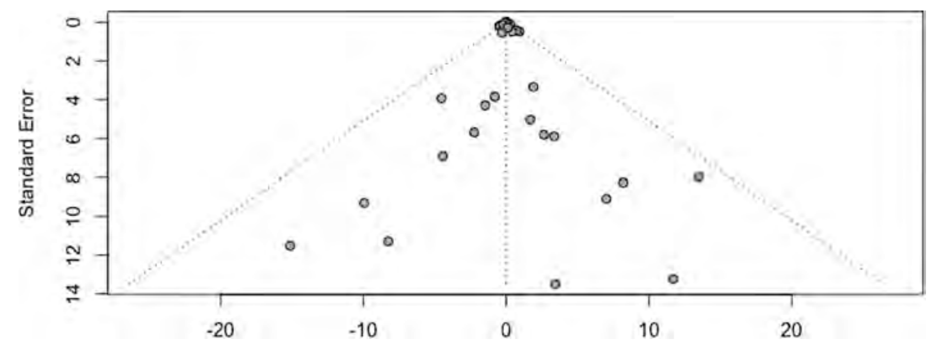

Fig. 6a. Funnel plots of all extracted beta coefficients for noise (in dB) and cognition.

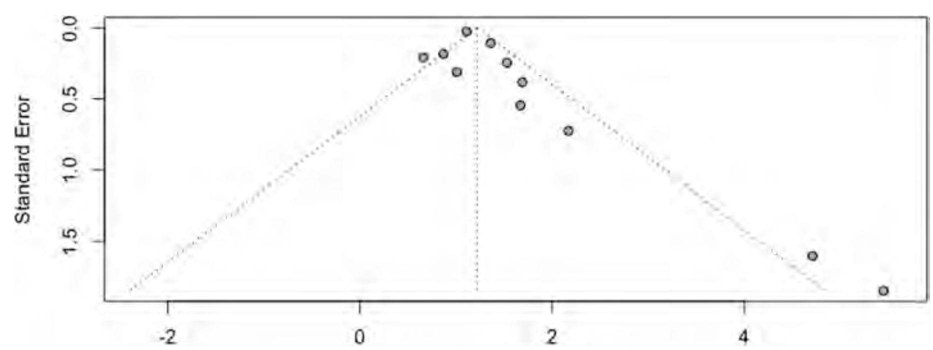

Fig. 6b. All extracted Odds Ratios for the impact of high noise exposure (reference low exposure, at variable definitions) on cognitive difficulties.

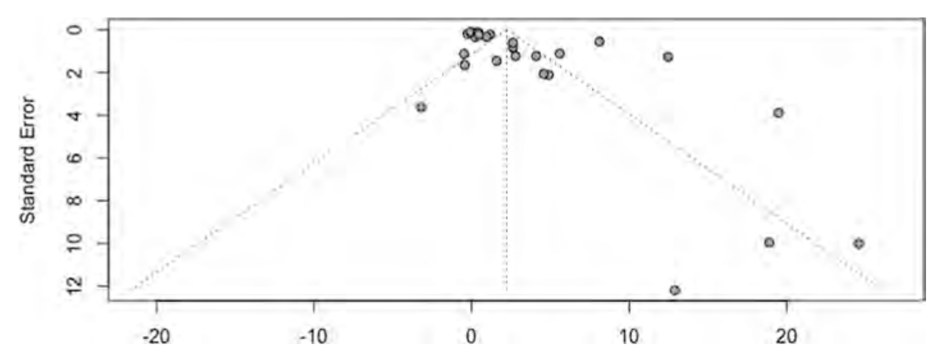

Fig. 6c. All extracted mean differences in performance on cognitive tasks for quiet compared to noisy environments (at variable definitions).

Credit authorship contribution statement

Rhiannon Thompson: Conceptualisation, Methodology, Data Curation (screening, selecting and extracting data from studies in review), Formal Analysis, Visualisation of data, Writing - original draft, Writing - review and editing. **Rachel B. Smith:** Conceptualisation, Methodology, Data Curation, Writing - review and editing. **Yasmin Bou Karim:** Conceptualisation, Methodology, Data Curation, Writing - review and editing. **Chen Shen:** Conceptualisation, Methodology, Data Curation, Writing - review and editing. **Kayleigh Drummond:** Data Curation, Writing - review and editing. **Chloe Teng:** Data Curation. **Mireille B. Toledano:** Conceptualisation, Supervision, Writing - review and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2021.106905.

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Audiological, Phonatory and Cardiac Correlates of Individuals Exposed to Low-Frequency Noise or at Risk of Vibroacoustic Disease

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Abstract

Introduction Low-frequency noise (LFN) is hazardous to hearing. Long-term exposure to LFN may lead to vibroacoustic disease (VAD), which not only affects a specific organ but the physiological function of entire systems, such as the auditory, phonatory, respiratory, and cardiac systems. Moreover, VAD may lead to many psychological problems and hence affect the quality of life.

Objective To investigate the adverse effects of LFN on hearing, acoustic and perceptual correlates of the voice, blood pressure, cardiac rate, and anxiety level.

Method A total of 20 subjects exposed to LFN and 20 not exposed to LFN were included, and a detailed case history was recorded. The patients were submitted to pure tone audiometry, otoscopic examination, acoustic and perceptual analyses of the voice, maximum phonation time, and an assessment of the s/z ratio. We also assessed blood pressure, and the results of a voice-related quality of life questionnaire and of the Hamilton anxiety rating scale.

Results The results indicate that LFN had an adverse impact on the high-frequency threshold. The present study found a significant difference in shimmer and harmonics-to-noise ratio (HNR) values. Few subjects had high blood pressure and showed the sign of anxiety on the Hamilton anxiety rating scale.

Conclusion Low-frequency noise has adverse effects on entire systems of the body and causes many psychological issues, which, in turn negatively affect quality of life.

Keywords
- anxiety
- hoarseness
- hearing loss
- blood Pressure

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Introduction

Noise is an unwanted sound that is detrimental to our auditory system. Low-frequency noise (LFN) ranging from 10 Hz to 500 Hz is hazardous to hearing and may cause permanent impairment. Long-term exposure to LFN may lead to vibroacoustic disease (VAD), which not only affects a specific organ but entire systems of the body, such as the auditory,[1–4] phonatory,[3,5] respiratory,[6,7] and cardiac systems,[7–9] as well as body metabolism,[10,11] and it can lead to psychological issues.[12,13] Excessive exposure to LFN results in abnormal growth of extracellular matrices (collagen and elastic), which may thicken blood vessels.[8] Hence, lower blood flow to the brain may cause dizziness,[1,4] vertigo,[1,2,4] headache,[2] depression,[12,13] reduction in concentration,[12] unusual tiredness,[7,12] and sleep disturbances.[10,11,13]

VAD and the Auditory System

Many studies[1,2,4] have discussed the adverse effect of VAD on the human and mammalian auditory systems. Studies[1,2] have reported that exposure to LFN mostly leads to high-frequency hearing loss and, if prolonged, it may gradually include the mid and low octave frequencies. In VAD, pressure in the eardrum increases due to LFN, resulting in unpleasant sensations in the ear, which affect the auditory system. Prolonged exposure to LFN leads to many histological changes[14–16] in the auditory system affecting cochlear function, increasing mitochondrial activity, and the production of free radicals. This increase in the levels free radicals reduce the cochlear blood flow and lead to excitotoxic neural swelling, causing the death of necrotic and apoptotic cells in the organ of corti. The longer the exposure to LFN, the greater the severity of the VAD symptoms.[1–4] Long-term exposure to LFN may also lead to the tinnitus[17,18] and affect the vestibular system.[19,20] A study[17] reported that the prevalence of tinnitus is 24% higher among individuals exposed to noise than among the overall population. Many studies[19–22] have provided evidence that exposure to LFN can give rise to vestibular deficiency, and one[19] has reported that LFN may damage the sacculocolic reflex pathway and damage the vestibular hair cells.

VAD and the Phonatory and Respiratory Systems

There are few articles on the effect of VAD on the phonatory[3,5] and respiratory systems.[6,7] Individuals working in the presence of LFN mostly abuse their voice[5] as they speak loudly for the auditory feedback. Prolonged vocal abuse leads to histological changes in the vocal folds and may give rise to infections and vocal pathologies.[23] Prolonged vocal abuse results in repetitive injuries to the laryngeal mucosa, which may lead to benign inflammatory lesions of the vocal cords.[23,24] Many studies[25–28] have reported that the prevalence of hyperfunctional voice disorders is higher in individuals with a history of vocal abuse.

There is a lack of studies on the effect of LFN on the human respiratory system; however, there is evidence from animal studies.[29–31] The respiratory cilia are composed of tubulin, and they are anchored to the actin cytoskeleton (CSK). With prolonged exposure to LFN, these cilia become shaggy, sheared, and clipped.[32] One study[33] found focal lung fibrosis on the autopsy of aircraft technicians exposed to prolonged LFN. Ferreira et al.[6] reported that a person exposed to LFN might develop respiratory disorders within the first four years of exposure and gradually progress into dyspnea and shortness of breath. The authors have also reported that these symptoms are independent of smoking habits.

VAD and the Cardiac System

In 1989, Araujo et al.[34] were the first to report the effect of LFN on the cardiac system of aircraft technicians. They used echocardiography (ECG) to assess pericardial thickening and reported that all aircraft technicians had abnormal pericardial or cardiac-valve thickening. Later, many studies[7–9,35–38] described and discussed the effects of VAD on the cardiac system. Pericardial thickening is the most prominent effect of VAD, and the cardiac cycle is affected by the thickening of the mitral and aortic valves. Due to this, blood flow is restricted from the left atrium to the left ventricle and then to the rest of the body.[7–9] A study[9] revealed that individuals with VAD most often suffer from sudden and violent tachycardia, which indicates sudden kinetic changes in the cardiac or pericardial rhythm.

Hypertension, Anxiety, and Psychological issues in VAD

There is evidence on the effect of prolonged exposure to LFN on blood pressure[10,11,38,39] and anxiety.[10,11,13,38,40] Many studies[11,12,41] have suggested that prolonged exposure to causes many psychological issues, such as mood swings, increased stress, irritation, annoyance, sleep disorders, and changes in behavior. Studies[38,39] have also revealed that LFN exposure may lead to the changes in blood pressure, most commonly high blood pressure. Most studies[40,41,43][superscript] report that individuals exposed to LFN develop high levels of anxiety. High levels of anxiety may be cause by different VAD symptoms.[40] The anxiety related to LFN exposure may be due to disturbance in daily activities, sleep, thoughts. High anxiety may also result from negative emotional responses, such as irritation, distress, and a wish to escape from the noise.[42,43]

Based on the review of the literature, we can see that VAD causes a plethora of symptoms and may affect the whole physiology of the body. In the recent literature, there are many studies[33–40] on the effect of VAD on the hearing and cardiovascular systems, and on psychological issues. On the other hand, the previous literature consists only of a handful of studies on the effect on the voice of prolonged exposure to LFN. After going through the previous literature[60–62], we were motivated to look into the adverse effects of VAD on the various systems and its correlation with the duration of LFN exposure. In the present study, we investigate acoustic and perceptual correlates of the voice, since in the previous literature most of the inference was drawn from animal model studies, not studies in humans. Therefore, the goal of the current investigation is to investigate the adverse effects of LFN on hearing, acoustic and perceptual correlates of the voice, blood pressure, cardiac rate, and anxiety level.

Methodology

Before data collection, consent was taken from all of the participants. All of the instrument analyses were performed using non-invasive procedures. In the present study, non-invasive instrumental analysis were conducted.

Participants

A total of 20 male subjects with ages ranging from 18 to 54 years (mean: 36.5 ± 10.4 years) who worked in noisy environments and 20 male subjects with ages ranging from 21 to 50 years (mean: 38.2 ± 9.67 years) working in non-noisy environments participated in the present study. We included subjects with a minimum of two years of working experience. Subjects with psychological, behavioral, neurological and other health-related issues were excluded. All the participants were recruited from a textile factory and gave written informed consent. The mean working experience of the noisy group was of 13.75 ± 9.01 years. The demographic details of the subjects exposed to LFN are described in ►**Table 1**. The mean daily working hours of the subjects was of 10.45 ± 1.14 hours. A detailed interview with the whole sample revealed a common habit of drinking tea five to six times per day on average. Seven subjects used to smoke (that is, more than four bidi/cigarettes per day), and all subjects had a habit of chewing tobacco while working.

Table 1 Age, years of work experience and daily working hours of the individuals exposed to low-frequency noise

Participants	Age (years)	Work experience in noisy situation (years)	Daily working hours
Participant 1	54	14	10
Participant 2	44	15	11
Participant 3	49	37	10
Participant 4	18	4	11
Participant 5	27	6	8
Participant 6	28	4	10
Participant 7	40	20	12
Participant 8	30	10	10
Participant 9	30	10	10
Participant 10	42	21	11
Participant 11	32	15	12
Participant 12	26	8	12
Participant 13	38	25	10
Participant 14	50	30	11
Participant 15	45	10	10
Participant 16	51	15	8
Participant 17	20	3	11
Participant 18	37	10	10
Participant 19	40	12	12
Participant 20	29	6	10
Mean ± standard deviation	36.5 ± 10.4	13.75 ± 9.01	10.45 ± 1.14

Tools and Instrumentation

Initially, we recorded the case history in detail, including the information regarding the duration of work, the daily exposure to noise, tinnitus, vertigo, and nausea, and we also asked questions that helped identify other health-related issues. To assess the hearing status, we performed pure tone audiometry (PTA) using the Elkon mini audiometer (Elkon Pvt. Ltd., Mumbai, Maharashtra, India). To assess the effect of LFN on voice, we performed an acoustic analysis using the Praat software (Paul Boersma and David Weenink, Phonetic Sciences, University of Amsterdam, Amsterdam, The Netherlands), and a perceptual analysis using the Buffalo III voice screening profile.[44]

To assess the effect of voice impairment on quality of life, we used the Voice-related Quality of Life (VRQOL) questionnaire.[45] The maximum phonation time (MPT) and the s/z ratio were assessed as an aerodynamic measure of the voice. Blood pressure and the cardiac rate were measured using the Omron HEM 7113 (Omron Corporation, Kyoto, Japan). In order to assess anxiety, we used the Hamilton Anxiety Rating Scale (HAM-A),[46] which consists of 14 questions scored from 0 to 4 (0: not present; 4: severe).

Procedure

Before data collection, noise levels were analyzed using a portable sound level meter (B&K 2250-L, Brüel & Kjær, Nærum, Denmark) three times a day randomly in the participants' workplace. The data were collected in two phases: first, the case history was recorded in detail, and it included health-related issues, changes in mood, the duration of work, daily exposure to noise, and the presence of tinnitus, vertigo, recruitment, and nausea. We further assessed the stress level (using the HAM-A), blood pressure, and cardiac rate. In the second phase, we conducted an outer-ear inspection using an otoscope, and PTA for the frequencies of 1 kHz, 2 kHz, 4 kHz and 8 kHz in a silent room with a minimal noise level. The silent room was located another building in the same campus due to the non-availability of a soundproof room/chamber. We made sure that the background noise was within permissible limits by measuring the noise level using sound level meter and applying the calibration factor as per the ANSI S3.-1999 (R2018) standard issued by the American National Standard Institute[47] for each participant. We could not include the frequencies of 500 Hz and 250 Hz in the PTA due to the higher calibration factor. The acoustic parameters of the voice were measured using the stimulus /a/. Along with these measurements, we further assessed the MPT, the s/z ratio, and the VRQOL.

Data Analysis

The data were analyzed using the Statistical Package for the Social Sciences (IBM SPSS Statistics for Windows, IBM Corp., Armonk, NY, US) software, version 20.00. The means and standard deviations were recorded, and the independent samples *t*-test was used to assess the mean differences regarding the parameters of the experimental and control groups. Multiple linear regression analysis was used to assess the effect of the years of working experience in environments with LFN and the amount of daily noise exposure on the hearing thresholds, acoustical voice parameters, anxiety level, and cardiac rate.

Results

In the present study, the factory's mean noise level in the subjects' working area was above 90 ± 5) dBA in three daily measurements made at different times. Descriptive analysis revealed that the subjects had a minimum of 3 years and a maximum of 37 years of experience working in noisy environments.

Effect of LFN on Hearing

An otoscopic examination revealed that the tympanic membrane was intact in all subjects. The hearing assessment revealed that all participants had poor threshold at high frequencies, and 3 of them had a dip at 4 kHz. The independent samples *t*-test revealed a significant difference between the right and left ear thresholds for all the frequencies between the experimental and control groups, as shown in ►**Table 2** and ►**Fig. 1**

The participants with longer exposure to LFN also reported the presence of high-frequency tinnitus and occasional vertigo. More than half of the population (that is, 16 subjects) reported tinnitus, but only 3 subjects reported bothersome tinnitus that caused them to have a disturbed sleep pattern. Eleven (55%) subjects reported intolerance to sounds which would be comfortable to a person not exposed to LFN. Multiple linear regression was calculated to predict the hearing loss based on the years of working in noisy environments and the daily hours of exposure. A significant regression equation was found for the frequency of 8 KHz in right and left ears, as shown in ►**Table 3**.

Effect of LFN on the Voice

The results revealed significant differences regarding shimmer ($p = 0.004$) and the harmonics-to-noise ratio (HNR; $p = 0.002$). ►**Table 4** shows a mean difference in the jitter values of both groups, which was not statistically significant. The multiple linear regression analysis was used to explore the effect of the years of work experience in environments with LFN and the daily hours of noise exposure on the acoustical parameters of the voice. A significant regression equation was only found for the HNR, as shown in ►**Table 5**.

►**Figure 2** shows that, regarding the voice, 55% ($n = 11$) of the sample had the normal quality, pitch, and intensity on the Buffalo III voice screening profile. However, the quality of the voice was mild in 20% ($n = 4$), moderate in 10% ($n = 2$), and severely hoarse in 5% ($n = 1$), whereas 10% had mildly breathy voice quality. Most participants ($n = 9$, 45%) had poor and limited pitch variation; however, only 6 (30%) had a limited intensity range. The analysis revealed a significant difference in the maximum phonation time ($p = 0.000$)

Table 2 Mean and standard deviation (SD) values for the right and left ear thresholds of both study groups for each frequency of the hearing assessment

Ear	Frequency	Group	Mean ± SD	*p*-value
Right	1 kHz	Control	24 ± 4.47	0.000
		Experimental	39 ± 5.02	
Left	1 kHz	Control	17 ± 2.51	0.003
		Experimental	38 ± 5.40	
Right	2 kHz	Control	24.75 ± 3.52	0.000
		Experimental	37.50 ± 5.05	
Left	2 kHz	Control	20 ± 2.80	0.000
		Experimental	38 ± 4.02	
Right	4 kHz	Control	25 ± 2.80	0.000
		Experimental	38.50 ± 4.38	
Left	4 kHz	Control	23 ± 2.82	0.001
		Experimental	39 ± 4.65	
Right	8 kHz	Control	26.25 ± 2.75	0.002
		Experimental	38.5 ± 5.22	
Left	8 kHz	Control	26 ± 2.22	0.000
		Experimental	40 ± 4.09	

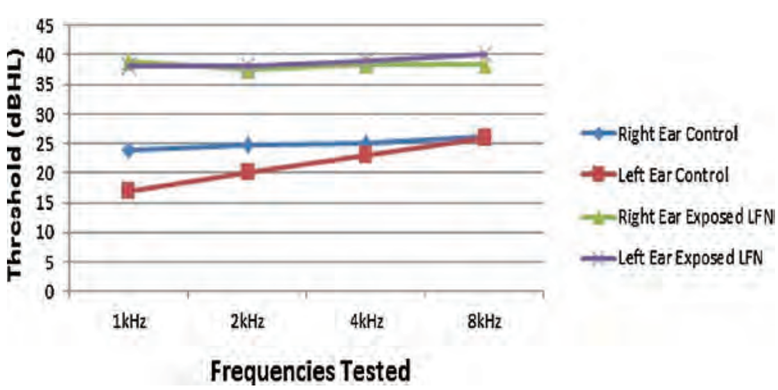

Fig. 1 Mean values of both groups for each tested frequency.

Table 3 Multiple linear regression analysis showing the effect of daily noise exposure and years of work in environments with low-frequency noise on the hearing thresholds

Variables		Model coefficient					
Dependent variables	Independent variables	Regression coefficient (B)	Standard error	Beta	*p*-value	R	R^2
Threshold of the right ear at 8 KHz	Daily noise exposure	0.513	1.85	0.067	.005*		
	Years of work in environments with low-frequency noise	0.41	0.23	0.042	0.03*	0.831	0.708
Threshold of the left ear at 8 KHz	Daily noise exposure	2.10	2.23	2.16	0.01*		
	Years of work in environments with low-frequency noise	0.33	0.28	0.26	0.04*	0.832	0.801

Note: *Significant at the level of 0.05.

Table 4 Mean and standard deviation (SD) values of the acoustic parameters of both groups

Acoustic parameter	Groups	Mean ± SD	*p*-value
F_0 frequency	Control	138 ± 10	> 0.05
	Experimental	122 ± 13	
Jitter	Control	0.45 ± 0.38	> 0.05
	Experimental	0.72 ± 0.68	
Shimmer	Control	3 ± 3	0.004
	Experimental	9.6 ± 3.2	
Harmonics-to-noise-ratio	Control	18 ± 5	0.002
	Experimental	12.33 ± 4	

between the individuals exposed to LFN (mean ± standard deviation [SD] = 13.65 ± 5.13 s) and not exposed to LFN (mean ± SD = 25 ± 7 s). Regarding the s/z ratio, it was higher than 1.40 in 9 (45%) participants, indicating laryngeal pathology.

On the VRQOL self-assessment questionnaire, most of the sample (n = 16, 80%) answered "No Problem in Voice". However, 3 (15%) participants reported "a small amount of problem", and 1 (5%) subject reported "a moderate amount of problem," as shown in ►**Fig. 3**.

Effect of LFN on Blood Pressure, Cardiac Rate, and Anxiety Level

All participants had normal blood pressure (systolic: mean ± SD = 134.95 ± 12.20; diastolic: mean ± SD = 85.9 ± 8.45). However, blood pressure was elevated 4 (20%) subjects and

Table 5 Multiple linear regression analysis showing the effect of daily noise exposure and years of work in environments with low-frequency noise on the harmonics-to-noise ratio

Variables		Model Coefficient					
Dependent variable	Independent variables	Regression coefficient (B)	Standard error	Beta	*P*-value	R	R^2
Harmonics-to-noise-ratio	Daily noise exposure	1.155	1.504	0.253	0.046*		
	Years of work in environments with low-frequency noise	0.010	0.169	0.020	0.004*	0.775	0.766

Note: *Significant at the level of 0.05.

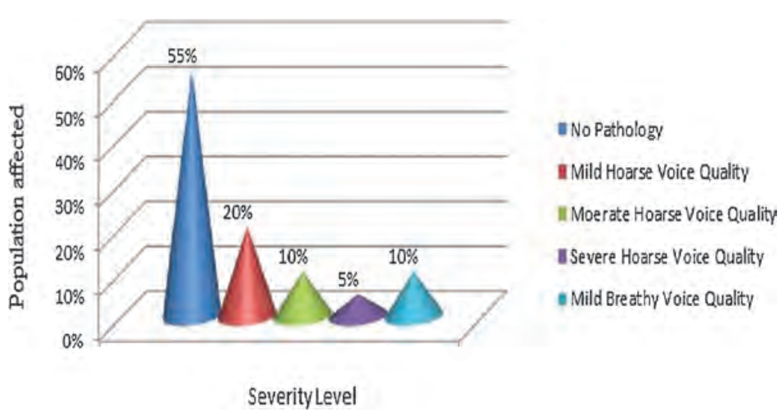

Fig. 2 Results of the Buffalo III Voice Screening Profile of individuals exposed to LFN.

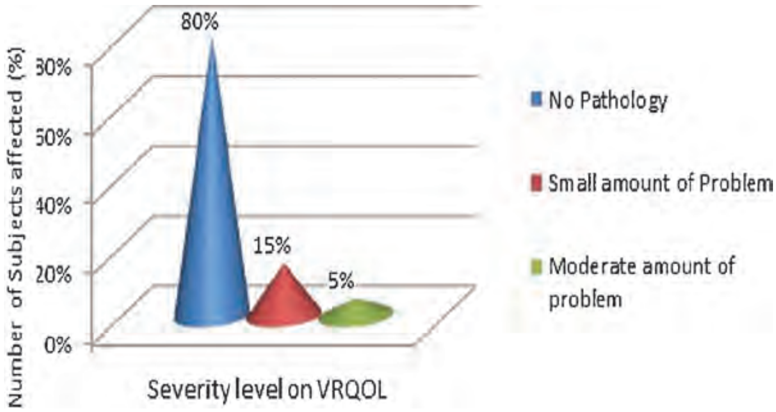

Fig. 3 Results of the VRQOL questionnaire.

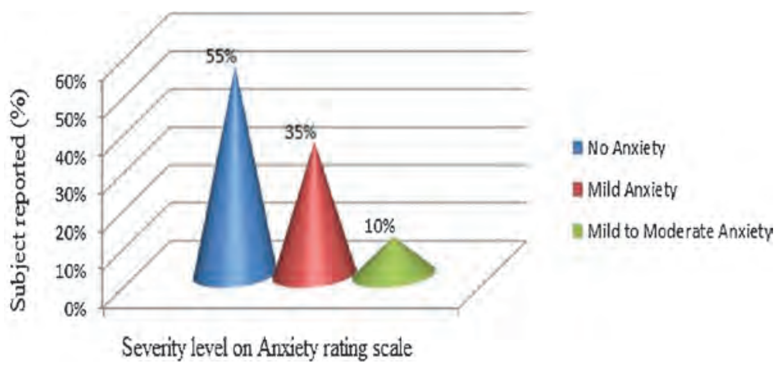

Fig. 4 Graphical representation of the HAM-A scale.

low in 1 (5%). The subjects with elevated blood pressure more than 20 years of LFN exposure. The results also revealed that most participants had normal cardiac rate (mean $\pm$ SD $= 75.55 \pm 10.43$), but it was high (> 100) in 2 (10%). Participants who had high cardiac rate had longer periods of exposure to noise. On the HAM-A, 55% ($n = 11$) of the sample was classified as having "no anxiety," 35% had "mild anxiety," and 10% had a "mild to moderate" level of anxiety, as shown in ►**Fig. 4**.

To identify the effect of daily noise exposure and working experience on the cardiac rate and anxiety level, we performed a multiple linear regression analysis, and we found a significant regression equation for both dependent variables, as shown in ►**Table 6**.

Discussion

The present study investigated the hearing, acoustical and perceptual parameters of the voice, cardiac rate, blood pressure, and anxiety level in individuals exposed to LFN, and the results revealed that prolonged exposure to LFN gradually affects systems of the body.

Table 6 Multiple linear regression analysis showing the effect of daily noise exposure and years of work in environments with low-frequency noise on the Anxiety level cardiac rate

Variables		Model coefficient					
Dependent variables	Independent variables	Regression coefficient (B)	Standard error	Beta	*p*-value	R	R^2
Anxiety level	Daily noise exposure	0.737	0.859	0.158	0.043*		
	Years of work in environments with low-frequency noise	0.382	0.109	0.042	0.03*	0.651	0.424
Cardiac rate	Daily noise exposure	1.879	2.188	0.176	0.003*		
	Years of work in environments with low-frequency noise	0.679	0.278	0.499	0.026*	0.744	0.696

Note: *Significant at the level of 0.05.

VAD and the Audiological Profile

In the present study, we conducted PTA at the frequencies of 1KHz, 2KHz, 4KHz, and 8KHz, and the result revealed that exposure to LFN gradually affects the high frequencies and leads to high-frequency hearing loss as was also reported by Nair and Kashyap.[1] They conducted a study with Indian Air Force personnel, and reported a high prevalence of high-frequency hearing loss among technicians (who are more exposed to LFN) compared with non-technicians. Similar results were reported by Senturia,[4] who conducted a study on long-term exposure to aircraft noise which revealed that individuals exposed to aircraft noise developed high-frequency sensorineural hearing loss. Reduced hearing sensitivity at high frequencies results in deterioration in speech perception,[48] which also worsen in the presence of noise.[49] In the present study, individuals exposed to LFN also reported high-frequency tinnitus and recruitment, similar to what was reported by Castelo Branco,[9] Nair and Kashyap,[1] Shargorodsky et al.,[17] and Mazurek et al.[18] Previous studies have reported that LFN affects the histological structure of the cochlea[14–16] and results in hearing deterioration, tinnitus, and recruitment, and that increases in the amount of LFN exposure affect the high frequency threshold[19–21]. The results of the present study are in lines with those of the studies conducted by Senturia,[4] Castelo Branco et al.,[3] Ribeiro and Câmara,[2] and Nair and Kashyap,.[1] who reported that the longer the exposure to LFN, the greater the severity of the VAD symptoms. The results of previous studies have also pointed that exposure to LFN could affect the vestibular system; however, in the present study we were not able to assess the vestibular system.

VAD & the Voice Profile

During literature review, we found only a handful of studies[60–62] on the effect of LFN on the phonatory system, and this motivated us to explore this subject. In the present study, we used acoustical and perceptual assessment methods to explore the effect of LFN on the phonatory system. We also used subjective assessment methods, such as the MPT and the s/z ratio. In the literature, the usefulness of the s/z ratio assessment method is the topic of debate; however, many previous studies[50–56] have used this method to assess the vocal status in different pathologies, and it may be helpful in screening the laryngeal pathology due to the acoustic properties of the sounds used.[57–59] In the present study, we found a significant difference in the shimmer and HNR values between the two groups. A difference was also found in jitter values, but it was not statistically significant. These could be due to the use of louder voice in the presence of LFN for the auditory feedback and to that fact that the frequent vocal abuse affects the physiology of the vocal folds, leading to changes in voice quality.[23] Similar results were reported by Ribeiro and Câmara.[2] On the other hand, Mendes et al.[5] found no evident changes in acoustic parameters in a population exposed to LFN, but F0 parameter increased significantly with the number of years of professional activity. Mendes et al.[5] did report changes in other acoustic parameters, but they were not statistically significant. These differences in results among different studies may be due to the different subject groups. In the present study, the subjects were recruited from a factory, and they did not wear any ear-protection devices, whereas Mendes et al.,[5] recruited airline pilots, who wear such devices. The present study further revealed that subjects exposed to LFN had decreased MPT and increased s/z ratio (higher than 1.40). The studies conducted by Mendes et al.[60–62] and Alves-Pereira et al.[63] also reported these results. The current study also revealed that hoarse voice quality may be due vocal abuse and unhealthy dietary habits, which is in line with the study by Castelo Branco.[9] In the present study, we also found that the HNR decreases as the of the exposure to noise exposure increases with time. This indicates that, as the noise exposure increases, the probability of developing vocal pathology also increases due to the continuous vocal abuse, which cause changes in the histological morphology of the vocal folds.[24]

Effect of LFN on Cardiac Rate, Blood Pressure and Anxiety Level

In the current study, we assessed the cardiac rate, blood pressure and anxiety level along with changes in the auditory and phonatory systems in individuals at risk of developing VAD. The study showed that subjects exposed to LFN are at a higher risk of having increased cardiac rate, which could disturb the cardiac cycle. Similar findings were reported by Marciniak et al.,[8] Castelo Branco et al.,[7] and Araujo Alves et al.[38] Increased cardiac rate may lead to an episode of sudden tachycardia.[9] The current study also showed that an increase in the exposure to noise has direct effects on the cardiac rate, that is prolonged exposure of LFN hampers and disturbs the functioning of the cardiac system, which s in line with the reports by Albuquerque e Sousa et al.,[35] Carmo et al.,[36] Marciniak et al.,[8] and Araujo et al.[37] In the present study, we also found that individuals with a longer exposure to noise showed increased anxiety levels. Similar results were discussed in the health statement of the County of San Diego,[11] the Department of Health of the Commonwealth of Australia,[10] and Beutel et al.[13] Our results also indicate that the anxiety level is affected by the increased level and duration of the exposure to noise. Increased anxiety levels may lead to changes in blood pressure or increased heart rate. Abbasi et al.[40] reported that high levels of anxiety may lead to hypertension and vice versa. The current study also revealed that most of the experimental group had hypertension, which is in line with the studies by Leon Bluhm et al.[39] and Araujo Alves et al.[38]

Conclusion

Based on the current study, we can conclude that LFN has adverse effects on the whole body. Prolonged exposure to LFN not only affects different systems, but also leads to psychological issues. In the present study we tried to assess the effect of LFN on the different human systems using various methods. We predominantly aimed to explore the effect LFN exposure on the phonatory system using acoustical and perceptual methods. From the results of the present study, we can infer that VAD affects different body systems as well as quality of life. The present is a preliminary study, and future studies will require extensive research in this field.

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Conflict of Interests

The authors have no conflict of interests to declare.

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Vibroacoustic Disease

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Vibroacoustic disease (VAD) is a whole-body, systemic pathology, characterized by the abnormal proliferation of extra-cellular matrices, and caused by excessive exposure to low frequency noise (LFN). VAD has been observed in LFN-exposed professionals, such as, aircraft technicians, commercial and military pilots and cabin crewmembers, ship machinists, restaurant workers, and disk-jockeys. VAD has also been observed in several populations exposed to environmental LFN. This report summarizes what is known to date on VAD, LFN-induced pathology, and related issues.
In 1987, the first autopsy of a deceased VAD patient was performed. The extent of LFN-induced damage was overwhelming, and the information obtained is, still today, guiding many of the associated and ongoing research projects. In 1992, LFN-exposed animal models began to be studied in order to gain a deeper knowledge of how tissues respond to this acoustic stressor.
In both human and animal models, LFN exposure causes thickening of cardiovascular structures. Indeed, pericardial thickening with no inflammatory process, and in the absence of diastolic dysfunction, is the hallmark of VAD. Depressions, increased irritability and aggressiveness, a tendency for isolation, and decreased cognitive skills are all part of the clinical picture of VAD. LFN is a demonstrated genotoxic agent, inducing an increased frequency of sister chromatid exchanges in both human and animal models. The occurrence of malignancies among LFN-exposed humans, and of metaplastic and displastic appearances in LFN-exposed animals, clearly corroborates the mutagenic outcome of LFN exposure.
The inadequacy of currently established legislation regarding noise assessments is a powerful hindrance to scientific advancement. VAD can never be fully recognized as an occupational and environmental pathology unless the agent of disease - LFN - is acknowledged and properly evaluated. The worldwide suffering of LFN-exposed individuals is staggering and it is unethical to maintain this status quo.

Keywords: cardiovascular thickening, echocardiography, respiratory drive, tumours, extra-cellular matrix, low frequency noise

Introduction

For the past two millennia, acoustic events have been associated with hearing impairment. Within the past 200 years, human civilization has been an ever-increasing source of acoustic energy, on par only with the amount of light that is produced on our planet. However, unlike electromagnetic radiation, where different frequencies are known to produce different health hazards, with acoustic energy no such information is available. Despite the substantial body of evidence indicating that acoustic phenomena impinges on more than just the ear, "noise" continues to be assessed based on the assumption that only what the individual *hears* is harmful (Alves-Pereira and Castelo Branco, 1999). The implication that an agent of disease has to be perceived to be harmful is ludicrous: x-rays, for example, are not perceived by humans, but are, nevertheless, a fully recognized health hazard.

In 1928, Laird published one of the first studies on the physiological effects of noise on typists (Laird, 1928), and since then, vast amounts of medical and biomedical studies have appeared in the literature (Alves-Pereira, 1999). In 1946, E. Dart, employed as a physician at the Ford aircraft engine manufacturing plant, in Detroit, MI, USA, described a set of symptoms observed in aircraft technicians (Dart, 1946). Rumancev, in 1961, describes the same collection of symptoms that he observed in a population of workers employed by a reinforced concrete factory, in the Soviet Union (Rumancev, 1961). Cohen, in the USA in 1971, reported on the medical complaints of boiler-plant workers, before and after the implementation of a hearing conservation program, and listed similar symptoms as Dart and Rumancev before him (Cohen, 1971). Grechkovskaia *et al.* speak of a “vibronoise pathology” in workers employed at an aircraft industry in Kiev, Ukraine (Grechkovskaia *et al.* 1997). Balunov *et al.* studied workers engaged in ferro-concrete production in St. Petersburg, Russia, under combined vibration, infrasound and noise, and concluded that this group had an increased morbidity (Balunov *et al.*, 1998). In 86 female textile workers, Magomedov *et al.* identified disturbances of the autonomic and central nervous systems that preceded hypoacousis, such as asthenovegetative and neurotic syndromes (Magomedov *et al*, 1997). Also in 1997, Izmerov *et al.* suggested the existence of a whole body response to infrasound (Izmerov *et al.*, 1997).

In 1979, the health of workers employed by the Portuguese Air Force, at an aircraft maintenance, repair and manufacturing plant (OGMA), was placed under the care of author Castelo Branco. While visiting all work-stations, he witnessed an aircraft run-up procedure and observed a technician walking about aimlessly, in what appeared to be an epileptic-like episode (Castelo Branco and Rodriguez, 1999). This prompted an investigation into the medical records of all aircraft technicians to determine how many had been previously diagnosed with late-onset epilepsy. The astounding number of 10%, versus the expected 0.2% found among the Portuguese population, was the basis for the in-depth neurological evaluation that ensued (Castelo Branco and Rodriguez, 1999).

Until 1987, aircraft technicians employed by OGMA received a series of medical tests that included brainstem auditory evoked potentials, brain MRI, cognitive tests and neurological examinations. All subjects were fully-informed volunteers. A large amount of neurological changes were identified in this group of aircraft technicians (Martinho Pimenta and Castelo Branco, 1999a) that included brain lesions and increased latencies in nerve conduction (Pimenta *et al.*, 1999), decreased cognition (Gomes *et al.*, 1999) and the appearance of archaic reflexes (Martinho Pimenta *et al.*, 1999a).

The First Autopsy

In 1983, the first patient in this group died suddenly, and an autopsy was not possible. This irritated Mr. Felipe Pedro, another aircraft technician, who had taken an academic interest in his health problems. The event prompted him to draw up a legal will, demanding that, upon his death, an autopsy be performed by Castelo Branco. Mr. Felipe Pedro worked as a ship machinist in the Portuguese Navy for 10 years prior to being hired by OGMA, in 1959, as an aircraft technician. A detailed description of the course of his medical evolution is given elsewhere (Castelo Branco, 1999a).

One early September morning in 1987, Castelo Branco received a phone call from Mr. Felipe Pedro who told him that he was very ill and was going to die. He asked Castelo Branco to meet him at the hospital so the autopsy could be performed. When Castelo Branco reached the hospital, Mr. Felipe Pedro was deceased. And the autopsy was performed. The findings so graciously provided to us by Mr. Felipe Pedro have been the basis for much of the subsequent research into noise-exposed workers.

Diagnosed with late-onset epilepsy in 1981, this man died at age of 58, of cardiac tamponade caused by a small infarct. His heart disclosed 11 small scars of previous silent ischemic events. Cardiac valves seemed swollen, and the pericardium surrounding the heart was greatly thickened. Coronary arteries were thickened, but not by the usual, and expected, artherosclerotic plaques. Instead, a continuous thickening of the

Table 1. Data from a group of 140 aircraft technicians (selected from an initial group of 306 workers), occupationally exposed to LFN (8 hrs/day, 5 days/week). Exposure time (in years) refers to the amount of time it took for 70 individuals (50%) to develop the corresponding sign or symptom (Castelo Branco, 1999b).

Clinical Stage	Sign/Symptom
Stage I-Mild (1-4 years)	Slight mood swings, Indigestion and heart -burn, Mouth/throat infections, Bronchitis
Stage II-Moderate (4-10 years)	Chest pain, Definite mood swings, Back pain, Fatigue, Fungal, viral and parasitic sk in infections, Inflammation of stomach lining, Pain and blood in urine, Conjunctivitis, Allergies
Stage III–Severe (> 10 years)	Psychiatric disturbances, Haemorrhages of nasal, digestive and conjunctive mucosa, Varicose veins and haemorrhoids, Duodenal ulcers, Spastic colitis, Decrease in visual acuity, Headaches, Severe joint pain, Intense muscular pain, Neurological disturbances

intima lined all vessel walls. Microscopic studies later revealed that much of the thickening was due to abnormal proliferation of collagen fibres. Two tumours were found, a Grawitz in the kidney, and a grade I, microcystic astrocytoma in the right parietal region of the brain.

Echocardiography

The autopsy findings of thickened cardiac structures led to the echocardiographic study of the population of aircraft technicians. All had thickened pericardia, and many also exhibited thickened cardiac valves (Marciniak *et al.*, 1999). A literature review revealed that Prof. Matoba, in Japan, had already identified pericardial thickening in some chainsaw workers (Matoba, 1983). Today, pericardial thickening in the absence of an inflammatory process, and with no diastolic dysfunction, is the hallmark of VAD (Holt, 2000). Pericardial thickening among LFN-exposed individuals has been anatomically confirmed through light and electron microscopy studies of VAD patient pericardial fragments (collected with patients' informed consent, during cardiac bypass surgery received for other reasons) (Castelo Branco *et al.*, 1999a, 2001, 2003a,b).

Echo-imaging equipment for cardiac structures has many manufacturers and many different models. Enhancing the view of pericardial thickening is not an established procedure. Thus, technician-dependent subjectivity is still inherent to this diagnostic method for VAD. Nevertheless, echocardiography is still the standard test for diagnosing VAD. Thickened cardiac structures have been observed in aircraft technicians (Marciniak *et al.*, 1999), commercial airline pilots and flight attendants (Araujo *et al.*, 2001), and in an islander population exposed to environmental LFN (Torres *et al.*, 2001). Thickening of cardiovascular structures has also been observed in LFN-exposed animal models (Castelo Branco *et al.*, 2003c).

The Clinical Stages of Vibroacoustic Disease

The evolution of VAD, as per years of occupational exposure, was defined in 1999 (see Table 1) (Castelo Branco,1999b). Establishing the evolution of VAD was not an easy task given the insidious nature of this pathology. In an initial group of 306 male aircraft technicians, all employed by OGMA for more than 10 years, rigorous selection criteria were applied as per Table 2. A group of 140 technicians (average age of 42 years, SD=10.4) remained after the application of selection criteria, i.e., 166 individuals were excluded.

OGMA, founded in 1918, possessed an on-site medical unit where all employees were seen when hired, and an individual medical file was

Table 2. Conditions for study population exclusion.

Conditions	Comments
Streptococcal Infections	Due to their propensity to induce extracellular matrix changes.
Diabetes mellitus	Same as above
Pre-existing Cardiovascular Disease	But not labile hypertensives, because it is suspected that this might be a measure of individual susceptibility, and because lesions are distinct from those caused by established hypertension.
Tobacco Abuse	Smokers of more than 20 cigarettes a day.
Alcohol Abuse	Drinkers with more than a litre of wine per day (10-12% alcohol content).
Drug Use	Users of any recreational or psychotropic drug.

opened. Subsequently, all annual examinations and medical complaints were recorded in the employee's medical file. The on-site medical unit offered employees a variety of medical specialties free of charge, such as internal medicine, cardiology, endocrinology, psychiatry, neurology, clinical and social psychology, dentistry, orthopaedics, general surgery, ophthalmology and otorhinolaryngology. An employee who required a specialist not available in the on-site medical unit, and wanted to make use of the National Health Care System, had to be referred to that specialist by one of the on-site general physicians. All medical information was thus recorded in all employee medical files.

The medical files of the 140 technicians were comprehensively and chronologically reviewed. Simultaneously, a sociologist and a social worker interviewed family and friends to obtain additional information on the individual's behaviour outside his professional activity. The methodology to obtain a correspondence between sign/symptom and years of occupational exposure was the 50% cut-off, i.e., the sign/symptom was included in the list if it was identified in 50% (N=70) of the study population. Thus, referring to Table 1, after 1-4 years of occupational exposure, at least 70 of these 140 individuals developed bronchitis, in smokers and non-smokers alike (smokers in study group: N=45). Or, after 10 years of occupational activity, at least 70 exhibited headaches and nose bleeds. It should be emphasized that these signs and symptoms are not mutually exclusive, and most VAD patients suffer from more than one or two of these clinical situations, simultaneously (Castelo Branco, 1999b).

Table 1 refers to the signs and symptoms developed specifically by aircraft technicians working the standard 8 hrs/day, 5 days/week. Not all LFN-exposed workers have this exposure schedule. For example, ship machinists can spend 3 weeks onboard ship (i.e., exposed to substantial LFN-rich environments) and 2 weeks at home (i.e., presumably not in LFN-rich environments) (Arnot, 2003). Other professional activities exist where the LFN-exposure time pattern is not the standard 8-hr/day exposure, such as with submarine and oil rig operators, and astronauts. In these cases, the evolution of signs and symptoms could be greatly accelerated. Moreover, since different LFN environments have unique frequency distributions, the fact that some frequency bands may be more predominant than others (i.e., concentrate more acoustical energy) can lead to the development of slightly different pathology. If the LFN exposure is environmental and/or leisurely, the standard 8hr/day model is also not applicable.

Associated Pathology

Other important pathologies were identified among these 140 aircraft technicians, but since they were not identified in 50% of the population, they were not included in Table 1. Nevertheless, their incidence is clinically important.

Some kind of respiratory insufficiency was found in 24 of the 140 professionals, 11 were smokers. In 10 of the 24 cases, a mere light physical effort was necessary to produce symptoms. Notably, only 45 of the 140 individuals were smokers, 38 of which had over 20 years of occupational LFN exposure.

Late-onset epilepsy was diagnosed in 22 individuals, some of whom saw their seizures subside when away from their workstation. Reflex epilepsy due to vibratory stimulus (Martinho Pimenta and Castelo Branco, 1999b) and visual stimulus was observed in two individuals. Auditory stimuli did not trigger seizures but, in some cases, triggered rage reactions and movement disorders (Martinho Pimenta and Castelo Branco, 1999c).

Balance disturbances were also a common complaint, identified in 80 individuals, although the severity of the balance disturbance ranged from dizziness to severe vertigo (Martinho Pimenta *et al.*, 1999b). Unique and sudden episodes of non-convulsive neurological deficit occurred in 11 individuals. These were diagnosed as cerebral ischemic vascular accidents, which was compatible with imaging studies. EEG and multi-modal evoked potentials showed considerable power changes that were in agreement with clinical psychological and neurological evidences. Delays in multi-modal evoked potentials (including endogenous), observed in all 140 patients, are a sign of progressive neurological deterioration and early aging process, as is the appearance of the archaic palmo-mental reflex, that affects about 40% of these 140 patients.

Other important pathologies observed among these 140 individuals were endocrine disorders, the most common being thyroid dysfunction (18 cases). The overall national Portuguese rate for adult thyroid dysfunction is 0.97% vs. the 12.8% identified in our group of 140 technicians. Similarly, diabetes was seen in 16 individuals (average age 39 years, SD=7.8) (11.4%), while the overall national rate for a similar age-group is 4.6% (Castelo Branco, 1999b).

Among the 140 professionals, 28 had malignant tumours. Five of these 28 individuals exhibited simultaneous tumours of different types. All CNS tumours (N=5) were malignant gliomata, and all respiratory system tumours were squamous cell carcinomas (5 in lung, 1 in larynx). Other tumours were found in the stomach (N=10), colon and rectum (N=9), soft tissue (N=1), and bladder (N=1) (Castelo Branco, 1999b). All digestive system tumours were low-differentiated adenocarcinomas. These data led to the investigation of the genotoxicity of LFN. In both human (Silva *et al.*, 1999a,b) and animal (Silva *et al.*, 2002) models, LFN induced an increased frequency of sister chromatid exchanges, effectively demonstrating that LFN is a genotoxic agent.

More recently, in 2003, a new pathological sign was identified among VAD patients: decreased respiratory drive (Reis Ferreira *et al.*, 2003a; Castelo Branco *et al.*, 2003d). To date, pulmonary function tests are normal in VAD patients, with the singular exception of the $P_{0.1}(CO_2)$ index, which is a measure of the inspiratory pressure (or suction) developed at the mouth, 0.1 seconds after the start of inspiration. This initial respiratory drive originates in the autonomic (or involuntary) pathway of the neural control of the respiratory function. By rebreathing CO_2, normal individuals would present a minimum six-fold increase of the $P_{0.1}(CO_2)$ index when compared to normal $P_{0.1}$. If the neural control of respiration is compromised, then a less-than six-fold increase would be expected in the $P_{0.1}(CO_2)$ index (Calverly, 1999; Cotes, 1993; Gibson, 1996). In VAD patients, all $P_{0.1}(CO_2)$ index values are

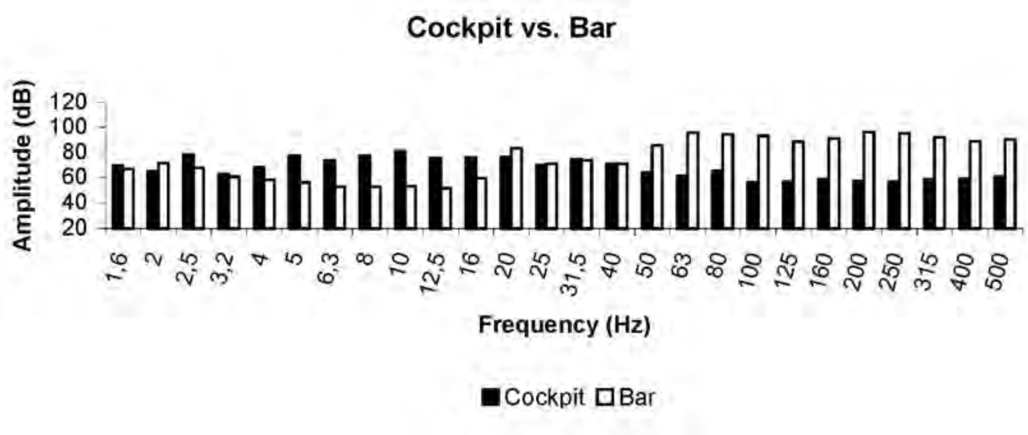

Figure 1. Frequency distributions, within the 1.6 – 500 Hz range, of the Airbus-340 cockpit in cruise flight and of a popular Lisbon Bar.

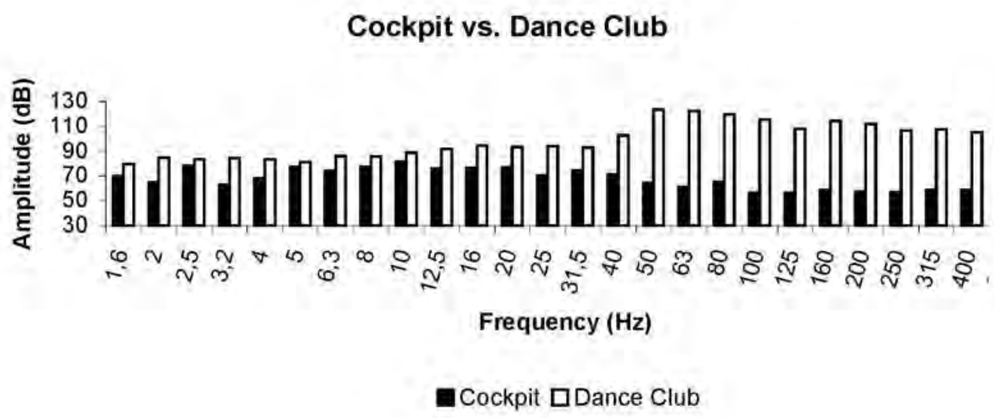

Figure 2. Frequency distributions, within the 1.6 – 500 Hz range, of the Airbus-340 cockpit in cruise flight and of a popular Lisbon Dance Club.

below 50%, when normal values would be above 60%.

Lastly, the issue of auto-immune diseases in LFN-exposed individuals. In the electron microscopy studies of VAD-patient pericardial fragments, non-apoptotic cellular death was frequently observed (Castelo Branco *et al*., 2003a). Instead, biomechanical forces seemed to be responsible for the images of burst cells, with live organelles and no surrounding plasma membrane. Under these circumstances, the appearance of auto-immune diseases in these patients is not unreasonable. Indeed, previous studies have shown that LFN exposure induces an accelerated onset of lupus in lupus-prone mice (Águas *et al.*, 1999a). Lupus has also been identified in flight attendants (Araújo *et al.*, 2001), and in entire families of islanders exposed to environmental LFN (Torres *et al.*, 2001). Vitiligo is another common finding, especially in the LFN-exposed islander population. Vitiligo is associated with immune changes of CD8 and CD4 lymphocyte populations. These immune changes have also been observed in LFN-exposed workers (Castro *et al.*, 1999) and animal models (Águas *et al.*, 1999b). Other authors have also corroborated the existence of auto-immune processes in noise-exposed workers (Matsumoto *et al.*, 1992, 1989; Jones *et al.*, 1976; Soutar *et al.*, 1974; Lippmann *et al.*, 1973).

Control Populations

One of the most difficult tasks of conducting studies related to LFN-induced pathology is the lack of viable control populations. By definition, in LFN-related studies, control populations are individuals who *are not exposed* to LFN.

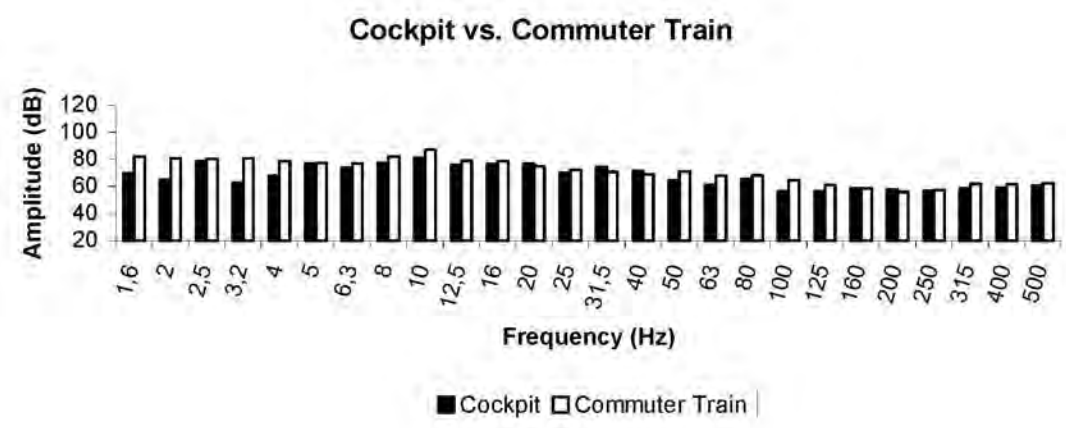

Figure 3. Frequency distributions, within the 1.6 – 500 Hz range, of the Airbus-340 cockpit in cruise flight and of a Commuter Train in transit during midday.

However, given the ubiquitous nature of LFN, control populations are not easy to find. Since the inadequate selection of control populations has given rise to conflicting results (ASTDR, 2001), it is pertinent to tackle this issue head on.

LFN is not legislated, and is therefore allowed to proliferate in almost every sector of human society. LFN exposure is not an exclusive feature of blue-collar workers. In fact, LFN exposure is an integral part of many leisurely activities and of many public transportation settings. Figures 1-5 and Table 3, compare the LFN levels of the cockpit of the Airbus-340 (Alves-Pereira *et al.*, 2001) with several locations commonly used by the public at large. Even the common passenger vehicle is a significant source of LFN (See Figure 5 and Table 3). So what is the profile of an adequate control population? Consider the following: control populations in any study are not usually monitored in terms of previous LFN exposure; thus, any control population of any study can be skewed because of the existence of a confounding factor – LFN. Moreover, considering the whole-body effects of excessive LFN exposure, compromising the cardio-respiratory and autonomic nervous systems, the degree of error may be significant.

In the specific cases where the investigation focuses on LFN exposed individuals in a certain industrial plant (for example), a control population selected merely on the criterion that they *do not work* at the industrial plant under study is invalid, because LFN exposure exists in many locations of our everyday life (See Figures 1-5). The most blatant example of inadequate selection of control populations is the Vieques Heart Study (ASTDR, 2001). Here, individuals who resided in an LFN-rich island (LFN produced by military training exercises) were compared to individuals who lived on another island. Living on another island and age-matching were the sole criteria for the selection of the control population in this study. This assumes that no LFN exposure exists on the

Table 3. Comparison of dBA and dBLin values in several, LFN-rich environments

Location	dBA	dBLin
Cockpit A-340*	72.1	87.3
Bar	98.4	104.4
Dance Club	110.3	127.5
Commuter Train	65.2	92.1
Subway	70.9	93.6
Common Automobile	71.2	100.8

*dBA values for the A -340 were obtained within the 6.3 -20000 Hz range. All other dB-level values were obtained within the 1.6 -5000 Hz range.

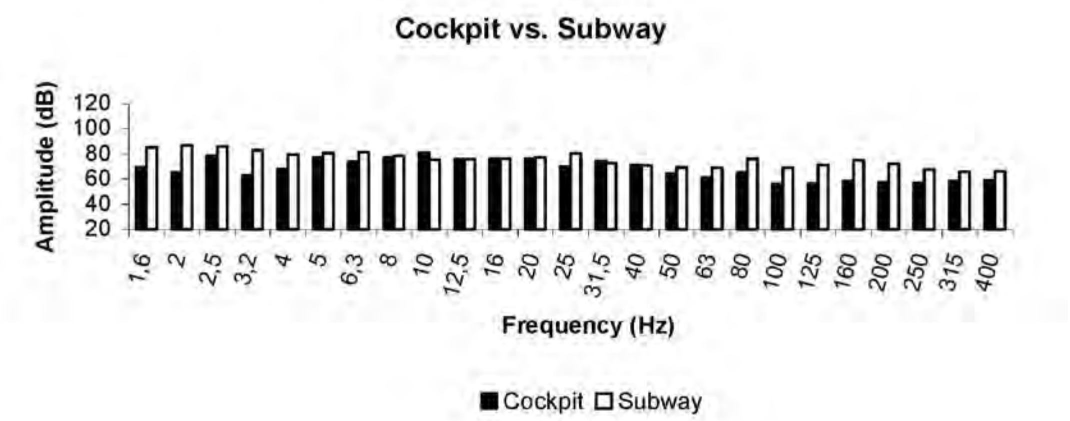

Figure 4. Frequency distributions, within the 1.6 – 500 Hz range, of the Airbus-340 cockpit in cruise flight and of a Lisbon Subway train, in transit.

other island, which is, of course, absurd, and is evidenced in the published results (ASTDR, 2001). Given what is known to date, control populations for LFN studies must be selected on the basis of negative VAD-related tests, (i.e., no pericardial nor cardiac valve thickening, and normal $P_{0.1}(CO_2)$ index), or must otherwise be considered non-controls.

Lastly, animal models also require control populations, and animal studies rarely monitor their acoustic environments. Hence, animal studies may also incorporate a significant confounding factor – LFN. The situation is further aggravated by the fact the many animal facilities are located in basements, where LFN components may reach significant amplitudes. If fine biochemical pathways are under study, and LFN is present but not monitored, how reliable are the results?

Two Anecdotal Stories of False Controls

The Technical Drawing Division, at OGMA, seemed to be an excellent location from which to select a comparison population, also employed at OGMA, but not exposed to occupational LFN. A 34-year-old male, with just this occupational profile, exhibited abnormal brain potentials, consistent with values obtained for VAD patients (Castelo Branco *et al.*, 1999b). Without his knowledge, his residential area, means of transportation and leisure activities, were investigated for possible sources of LFN noise. None were identified. Upon inquiry, his family and friends described him as reserved and quiet, but with sudden episodes of verbal aggressiveness, normally triggered by acoustic events. He was intolerant of any type of sound, including music and, like many others diagnosed with VAD, would complain of “hearing too much”. A later audiogram disclosed losses in the lower frequencies, as with other VAD patients. All other VAD-related diagnostic tests came back positive: brain MRI revealed hyperintense foci in T2 of the deep white matter, and echocardiography revealed mitral valve and pericardial thickening. But where was he being exposed to noise? During the neurological examination, which revealed the existence of the palmo-mental archaic reflex, the man finally explained: his parents owned and operated a water mill, and lived in a house directly above. The permanent low hum of the operating water mill was a constant in his home, where he lived until the age of 26. Unfortunately, the mill has since been closed down, and acoustic evaluations of the mill in operation are no longer feasible.

Another interesting case is that of a 50-year-old executive director, who has worked in a Lisbon bank for the past 30 years. Apart from the usual air-heating and -cooling office devices, and urban traffic, the LFN exposure of this individual was not thought to be significant. However, echocardiography disclosed thickened pericardium and cardiac valves. The $P_{0.1}(CO_2)$ index value was below 30%. No symptoms were reported. Where was he being exposed to LFN? He lived in Montijo, a town across the River

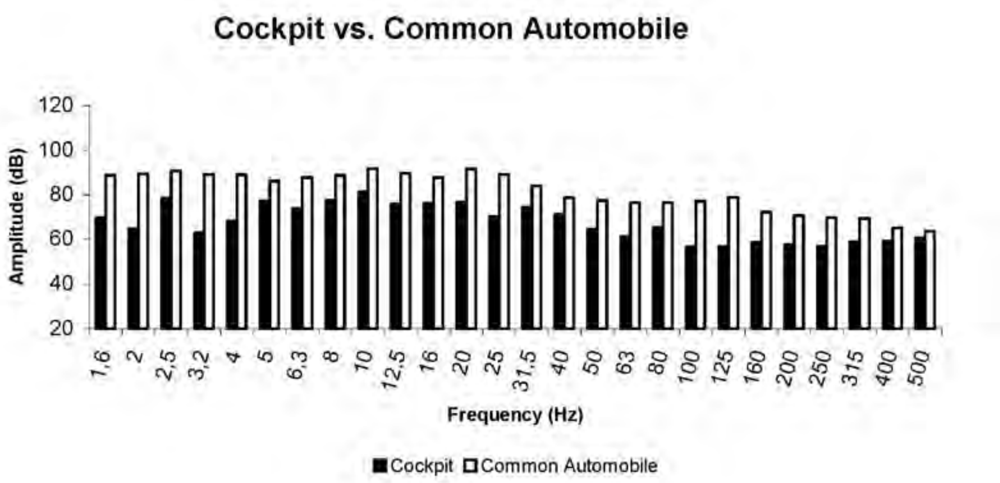

Figure 5. Frequency distributions, within the 1.6 – 500 Hz range, of the Airbus-340 cockpit in cruise flight and of a Common Automobile (Fiat Punto).

Tagus, and his daily car commute in heavy rush hour traffic takes 3 hours, approximately 100 Km. His cars have been equipped with diesel engines. In 1990, he restored his house in Galiza, Spain, just north of the northern Portuguese border and, since then, drives up there every weekend, approximately 400 Km each way. On a weekly basis, this man covers more 1500 Km in his diesel-engine cars. Figure 5 compares the frequency distribution of a gasoline automobile with that of the Airbus-340 cockpit. The data strongly suggest that the source of this man's LFN exposure is the large amount of hours spent driving. Acoustical studies in his specific car models are still underway.

Misdiagnosis of Vibroacoustic Disease

Stress-related syndrome

One of the most common commentaries about the signs and symptoms included in the Mild and Moderate Stages of VAD is their similarity to many generalized stress-related syndromes (Table 1). Although a cursory view might suggest this, a more in-depth approach demonstrates that this is not the case. VAD is specifically characterized by an abnormal proliferation of extra cellular matrices in the absence of an inflammatory process. Lowered cortisol levels and elevated peaks of circulating norepinephrine were observed in LFN-exposed workers (Sobrinho *et al.*, 1989), as well as, changes of auditory evoked responses (Castelo Branco, 1988) and of endogenous potentials that were correlated with CNS lesions - hyperintense foci in T2 of the subcortical and periventricular white matter, basal ganglia and brain stem (Pimenta *et al.*, 1999). To the authors' knowledge, this is not consistent with stress-related syndromes reported in the medical literature.

LFN exposure is more analogous to extreme stress situations, where similar brain lesions and cognitive impairment have been observed (Martinho Pimenta *et al.*, 1992). Also, disseminated intravascular coagulation is frequently the only abnormal autopsy finding in young paratroopers, deceased during military training exercises - an extreme stress situation – giving credence to the popular expression, "it was a blood-curdling experience" (Castelo Branco, 1992). In LFN-exposed workers, an increased rate of platelet aggregation has been identified, simultaneously with other LFN-induced pathology (Castelo Branco *et al.*, 2003e). Hence, regarding VAD as some generalized stress syndrome is not a tenable position, given its inconsistencies with what is known to date about generalized stress syndromes.

Malingering

Another common occurrence among VAD patients is the incredulity of physicians when confronted with complaints involving almost all organs and systems. OGMA medical records show that some physicians scribbled "malingerer" on the side. In a candid exposure of his medical condition, Mr. Jonathan Arnot, age 40, a ship machinist from Scotland and diagnosed with VAD, wrote how the suspicion of

malingerer greatly affected his life:
"I had often been suspected of malingering (…) The social implications of being considered a malingerer, even on behalf of family members employed within the health industry, were quite demoralizing. (…) Without a diagnosis I was left in a no-man's-land where none of the medical specialists could suggest treatment. I felt I was left to see whether my symptoms developed further into an accepted illness, or if they would just resolve themselves with the passage of time. (…) I felt that doctors prejudged my case and assumed that I was either looking for a sick note to have time off work, or that I was trying to build a case to sue someone. Neither of which was anywhere near the truth, I simply could not afford to fall ill (…) Loss of self-esteem, and loss of standing in the eyes of my children and friends must also be taken into account. Social exclusion due to the lack of spending cash, and the emotional effect of the constant suggestion that I was just malingering are merely a few of the actual costs of falling ill with an occupational illness that is not yet proscribed in the UK." (Arnot, 2003).

Mr. Arnot exhibited very thickened cardiac structures (particularly the pericardium), a $P_{0.1}(CO_2)$ index of 38%, and increased latencies of P3 endogenous potentials, all consistent with the VAD clinical picture.

In general, physicians are not sufficiently knowledgeable to question the patient as to his/her occupation. Even if the patient works in the home, the residential location is rarely questioned in terms of acoustic environment. In fact, the insistence that acoustic phenomena only affect humans via the auditory system is helping to jeopardize the health of many young men and women. What neurologist sends a patient diagnosed with epilepsy to receive an echocardiogram? Skepticism as to the existence of a whole-body pathological entity caused by acoustic phenomena has been immense (von Gierke and Mohler, 2002). And yet, for decades, scientists have been gathering evidence supporting just that notion (Alves-Pereira, 1999). Sometimes, scientists say they first encountered VAD within the military in the 1970s (Brenner, 2003). Additionally, some VAD cases have been misdiagnosed as Chronic Fatigue Syndrome.

Dose-responses

Dose-responses for LFN exposure have not yet been established. Waiting for dose-response values to accept the existence of a disease does not seem to be an ethical, nor logical, course of action. In truth, obtaining dose-response values for LFN-exposed humans, considering its aforementioned ubiquitous nature, is a daunting task. Dosimeters specifically designed to evaluate LFN have not yet been developed and, as previously mentioned, legislated noise assessment procedures do not contemplate LFN as a hazard. Therefore, LFN dose-response values for humans are, most probably, some years (and Euros) away. However, in LFN-exposed animal models, insight into dose-responses has already been obtained (Castelo Branco *et al.*, 2003c). In Wistar rats exposed to continuous LFN for 48 hours, and then kept in silence for up to 7 days, tracheal epithelia of exposed and controls only became indistinguishable after 7 days of post-exposure silence (Castelo Branco *et al.*, 2003c, 2003f). Wistar rats that were gestated and born in LFN, and subsequently kept silence for one year, still exhibited visible and dramatic damage of respiratory epithelia after the year in silence (Castelo Branco *et al.*, 2003c, 2003g). The implications of these studies are far-reaching and speak for themselves, especially if one considers that many female workers carry their pregnancies to term while working in LFN-rich environments.

As a final note on dose-responses, it must be recognized that different organic tissues possess different acoustic properties, i.e., the acoustic impedance of lung tissue is different than that of the liver, and the resonant frequency for the brain is different than that for the bladder. Thus, dose-responses must be established on the basis of the frequency of the acoustic event. An individual working in a LFN environment where there is a predominance of infrasound (<20 Hz), will develop slightly different pathological features than an individual who works in an environment where the acoustic energy is predominantly concentrated in the 50-100 Hz range. Hence, the issue of dose-responses must always be carefully approached.

Prevention

Previous studies have indicated that approximately 30% of the studied LFN-exposed individuals do not develop severe stages of VAD, although they exhibit mild forms of Stage I and II symptoms (Castelo Branco, 1999b; Castelo Branco and Rodriguez, 1999). This *is not* equivalent to stating that 70% will develop Stage III disabilities. The foremost concern is to prevent the development of disabilities that incapacitate individuals for further professional activity. Studies have indicated that, without prevention, approximately 5% of occupationally LFN-exposed individuals develop pathologies severe enough to require early disability retirement (Castelo Branco *et al.*, 1999b).

At OGMA, from 1980 to 1989, 21 aircraft technicians received compulsory early disability retirement. In 1989, on the heels of the echocardiography results based on 1987 autopsy findings (see above), a screening and monitoring medical protocol was developed for all LFN-exposed personnel. All incoming job candidates received echocardiograms as part of the routine physical examination. If pre-existing thickening of cardiac structures were identified, incoming job candidates would not be hired for jobs that implied working in LFN-rich environments. All LFN-exposed employees who already worked at OGMA began to receive annual echocardiograms, endogenous evoked potentials, and blood pressure was closely monitored. If and when LFN-exposed workers developed very thickened cardiac structures, and/or shifts in the P3 endogenous component to frontal positions, and/or difficult to control and unstable (labile) blood pressure, then they were removed from the LFN-rich work environment and placed at another, non-LFN-rich workstation. From 1989-1996 there were zero compulsory early disability retirements among LFN-exposed personnel (Castelo Branco *et al.*, 1999b).

Recovery periods should also be an integral part of any prevention programme against LFN-induced pathology. For personnel that *must* remain more than the usual 8 hours within a LFN-rich environment, extended recovery periods, i.e., periods away from the LFN-rich environment, should be mandatory. Acoustic materials that impede the propagation of LFN are also in development by several teams worldwide, and might provide future answers to protect workers form this agent of disease. Lastly, it should be strongly emphasized that the development of LFN-induced pathology is caused by a *cumulative* effect of LFN exposure, and whether the source is occupational, or not, is irrelevant to the biological organism. Moreover, the evolution of VAD will be directly linked with the overall exposure received from *all* LFN-rich environments to which the individual is exposed, occupational and/or environmental and/or leisurely.

Current Working Hypotheses

Studies that describe acoustic environments merely in terms of an overall dB-level cannot be scientifically compared to those that provide frequency distributions analysis.

Figures 4 and 5 compare the frequency distribution obtained in the cockpit of the Airbus-340 at cruise flight, with that obtained within a subway and a common passenger vehicle, respectively. See Table 3 for overall average values. For the subway, the dBA-level was 70.9 and for the car it was 71.2. These acoustical environments are considered comparable by the scientific community at large. In fact, they are not. dBLin levels were 93.6 for the subway and 100.3 for the car. The difference between dBA and dBLin levels, and the lack of usefulness of dBA measurements within the context of LFN-induced pathology, has been extensively discussed elsewhere (Alves-Pereira *et al.*, 2003a; 2003c; Alves-Pereira, 1999). The dBA value measures the overall average amplitude of the acoustical energy that is being captured (i.e. heard) by the human auditory system, and its usefulness is directly (and exclusively) related to the avoidance of hearing impairment. The dBLin value measures the overall average amplitude of the acoustical energy present in the environment, i.e., it measures the amplitude of what is actually present, and not just what can be heard. Looking at the distributions of both environments (Figures 4, 5), it is clear that within the 1.6-500 Hz range, the car has higher levels at all bands than the cockpit. This is not the case with the subway. Hence, two situations arise: a) it is not scientifically sound to compare the results of noise-related studies that describe their acoustical environments merely in terms of a dB-level measurement (i.e., without a frequency spectrum analysis), and b) the results of noise-related studies that do not report the frequency distribution of their acoustical environments cannot be compared to those that do.

Individual susceptibility is a confounding factor

Individual susceptibility was identified early on as a important factor influencing symptom severity, and clinical evolution (Castelo Branco, 1989). Several parameters were evaluated, such as blood and tissue compatibility markers, in order to search for a LFN susceptibility indicator. To date, none have been formally identified (Castelo Branco and Rodriguez Lopez, 1999). Animal models gestated and born in LFN-rich environments still exhibit severe respiratory tract damage, even after one year of post-birth continuous silence (Castelo Branco *et al*., 2003g). Moreover, they also exhibit behavioral differences when compared with those LFN-exposed animal models that were not gestated in LFN-rich environments. Hence, it is suspected that the situation of the individual's mother during pregnancy is one factor (of perhaps several) that may substantially contribute to an increased individual susceptibility to LFN. In ongoing research projects, the VAD-questionnaire now includes questions pertaining to this matter. If occupational LFN exposure is the focus, then non-occupational LFN exposure can also introduce a confounding factor. As is shown in Figures 1-5, LFN is ubiquitous. Hence, VAD-related questionnaires must explore *all* habitual and non-habitual locations where individuals may be exposed to LFN, including *in utero*.

LFN environments with acoustical energy predominantly within the infrasonic range (<20 Hz), accelerates the rate of pericardial thickening.

In 1999, volunteer commercial airline pilots and flight attendants received echocardiograms within the scope of VAD-related studies. Despite equal time of occupational activity, pilots disclosed a faster rate of pericardial thickening than did flight attendants (this was not a gender related feature since male flight attendants also participated) (Araújo *et al.*, 2001). In a subsequent acoustical analysis of both cockpit and cabin, the cockpit revealed statistically significant higher levels of infrasound than in the cabin (Alves-Pereira *et al.*, 2001). Infrasound in the cockpit varied with altitude, airspeed and aircraft model, which indicates that much of the infrasonic energy present in the cockpit is due to the impact of the airflow on the leading edge of the aircraft (Alves-Pereira *et al.*, 2001).

The onset of auto-immune diseases is accelerated by LFN exposure.

As discussed above, in the Associated Pathology of VAD, auto-immune diseases, particularly lupus, are very common among LFN individuals (Torres *et al.*, 2001; Araújo *et al.*, 2001; Matsumoto *et al.*,1992, 1989; Jones *et al.*, 1976; Soutar *et al.*, 1974; Lippmann *et al.*, 1973). One of the reasons may be the presence of non-apoptotic cellular death, with no inflammatory process, seen in the pericardial fragments of VAD patients (Castelo Branco *et al.*, 1999a, 2001, 2003a,b).

The respiratory system is a target for LFN.

Four VAD patients had atypical cases of pleural effusion that persisted in spite of therapy. Three of these cases were of unknown origin, although the fourth may have been caused by diphenylhydantoin (Castelo Branco, 1999a). The follow-up recovery periods were very prolonged, even in the case where diphenylhydantoin was suspended. Treatment took several months, and recovery was not only slow and irregular, but no conclusion was ever reached about the aetiology or choice of treatment. In the 1987 autopsy, focal lung fibrosis was identified, however no importance was attributed to this finding since chemicals, fumes and dusts were assumed to be present in this man's occupational environment (Castelo Branco, 1999a). In 1992, still concerned about the enigmatic cases of pleural effusion, animal models were used to study the respiratory tract response to LFN exposure. In LFN-exposed rodents, the amount of tracheal cilia was visibly reduced, and subsequent formal morphometric studies confirmed this feature (Oliveira *et al.*, 2002). Tracheal subepithelial fibrosis was also identified (Castelo Branco *et al.*, 2003c). Structural changes of the lung parenchyma included irregular distribution of thickened alveolar walls, dilated alveoli, and irregularly distributed fibrous foci (Castelo Branco *et al.*, 2003c). Pleural cells lost their phagocytic ability, and the pleural parietal leaflet had a marked reduction in the amount of microvilli per mesothelial cell (Oliveira *et al.*,1999). Subsequently, respiratory function tests and high resolution CT scan of the lung were administered to LFN-exposed workers, with and without respiratory symptoms. Focal lung fibrosis and air-trapping were identified in these workers, independent of the existence of respiratory complaints (Reis Ferreira *et al.*, 1999). Other authors have described the immediate subjective effects of large amplitude LFN tones on the respiratory system that included coughing, gagging sensation, and awareness of chest wall pressure (Mohr *et al.*, 1966; Cole *et al.*, 1966). An in-depth review of noise and the respiratory system has been reported elsewhere (Alves-Pereira *et al.*, 2003c).

LFN-exposure specifically causes squamous cell carcinomas of the respiratory tract.

To date, 100% of the respiratory tumours in VAD patients have been squamous-cell carcinomas: 10 in the upper right lobe of the lung (7 smokers) and 2 in the glottis (1 non-smoker) (Castelo Branco, 2001). This hypothesis has been further corroborated by the observation of metaplasia and displasia in the respiratory epithelium of LFN-exposed Wistar rats (Castelo Branco *et al.*, 2003c; 2003g). In the general population, squamous cell carcinomas of the lung account for 40% of all lung tumours (Skuladottir, 2001). However, cancer-related epidemiological studies do not usually describe the breakdown of tumour-type, which is very unfortunate. Global cancer statistics, without a breakdown of tumour-type, do not contain the essential, and crucial, information required for any in-depth statistical study, and the results can be misleading. Among VAD patients, the incidence of lung cancer, in general, is about the same as that of the Portuguese population, but in VAD patients, *all* tumours are located in the upper right lobe, and *all* are squamous-cell carcinomas (Castelo Branco, 2001). This is not equivalent to saying that all squamous-cell carcinomas all triggered by LFN-exposure, because certainly other agents might also induce the appearance of this type of respiratory tract tumour. What the date *does* demonstrate is that LFN-induced respiratory tract tumours are all of a single type: squamous cell-carcinomas.

Actin and tubulin based structures are particular targets for LFN.

Microvilli are composed of actin filaments, as are the streocilia in cochlear auditory hair cells. In LFN-exposed animals, both cochlear stereocilia and respiratory tract brush cell microvilli become fused structures (Castelo Branco *et al.*, 2003c, Alves-Pereira *et al.*, 2003b). A first approach might suggest that the commonality of these structures may be their finger-like, somewhat cylindrical shapes. However, cilia, found in the respiratory tract and in the pericardium, exhibit an entirely different behavior in the presence of LFN. Cilia in the pericardial fragments of VAD patients simply cease to exist (Castelo Branco *et al.*, 2003a,b; 2001; 1999a). In the respiratory tract of LFN-exposed animals, cilia appear sheared, as if clipped by scissors, and some images even captured these apparently sheared cilia lying upon the epithelial surface (Castelo Branco *et al.*, 2003c). Shaggy cilia and completely bald ciliated cells were also observed in LFN-exposed rodents. In two VAD patients (one non-smoker), scattered areas of damaged tracheal cilia were identified, and multiple ciliary axonemes were seen surrounded by the same membrane (Reis

Ferreira *et al.*, 2003c).

Elevated annoyance levels to noise are a sign of previous, excessive LFN exposure.

Cochlear stereocilia are actin-based structures that, in Wistar rats, fuse as a response to LFN exposure (Castelo Branco *et al.*, 2003c). Rats are particularly sensitive to the sound of a "blown kiss" and react by jerking their heads and becoming tense. After LFN-exposure, the "blown kiss" causes them to rise on their hind legs, often falling backward, with tremors. Fused cochlear stereocilia, if it also occurs in humans, may explain the unusual auditory complaints of VAD patients, such as, "I hear too much; I can't stand any type of noise, not even music" (Castelo Branco,1999b). If fused among themselves and to the tectorial membrane, cilia cannot freely vibrate as is intended when the sound pressure wave is transduced within the cochlea (Alves-Pereira *et al.*, 2003c). In fact, by becoming a rigid structure, any attempt at vibrating them might, understandably, produce discomfort. How closely related this phenomenon is to the concept of "annoyance" is still unclear. However, a relationship is clearly suggested, especially since annoyance has already been specifically associated with the presence of LFN (Persson-Waye and Rylander, 2001).

The whole-body response to excessive LFN exposure can be explained by principles of biotensegrity.

At a cellular level, the pericardial mesothelial-cell (MC) layer exhibits a peculiar morphological behaviour. The MC layer consists of a one-cell-deep surface, and is in direct contact with the pericardial sac. Hence, it is critical to the sliding effect necessary to an intact cardiac cycle. MC interconnect laterally with each other via cytoskeletal intermediate filaments and desmosomes. In pericardial fragments obtained from VAD patients, MC are seen in a process of extrusion from the surface layer into the pericardial sac (Castelo Branco *et al.*, 2003a,b). Desmosomes are no longer evenly distributed along the lateral edges of MC, and instead are concentrated, in groups of more than two, in the upper portions of the MC lateral borders. The lower portions seem to be forming gaps, with great plasticity, in which microvilli are identifiable (Castelo Branco *et al.*, 2003a). Biotensegrity systems can absorb external forces, and redistribute them throughout a network of tension and compression elements, but with no torque or bending moments (Wang *et al.*, 1997). Consider the MC layer as a structural surface composed of individual viscoelastic elements (the MC interconnected by cytoskeletal intermediate filaments and desmosomes) and that has to cope with abnormally large mechanical forces. Extrusion of MC into the pericardial sac strongly suggests that the MC layer is attempting to maintain the structural integrity, despite the abnormal biomechanical conditions.

Final Commentary

The agent of disease has already been identified – Low Frequency Noise.

Specific LFN effects have already been well defined: abnormal growth of extra-cellular matrices, in the absence of an inflammatory process, seen in both cardiovascular and respiratory system structures, in both LFN-exposed human and animal models.

The genotoxicity of LFN exposure has been demonstrated in both human and animal models.

Non-invasive diagnostic methods have already been defined: echocardiography to visualize thickened cardiac structures, $P_{0.1}(CO_2)$ index to measure the dramatically reduced respiratory drive, and evoked potentials that disclose important topographical changes and increased latencies in the P3 and N2 components, both indicative of cognitive impairment.

Large-scale epidemiological studies are still unpublished, in-depth studies of LFN-induced physiopathology are lacking, and case-control studies have not yet appeared in the medical literature. In fact, to the authors' knowledge, no other independent team has published results on echo-imaging studies on LFN-exposed individuals. Why? One of the main (scientifically-related) reasons is that LFN-induced is not "high-priority" topic in most scientific forums, hence grant approval rate for LFN-related studies is very low. Other, more political and financial reasons exist, however they are, of course, beyond the scope of this report.

The bottom line is: VAD is not acknowledged as a pathological entity, and individuals who exhibit VAD clinical pictures are malingerers (if workers) or neurotic (if females and/or housewives). At best, they are considered "overly sensitive" individuals. Moreover, since LFN exposure is not considered a health hazard by the authorities, it is rarely evaluated. Additionally, LFN-related studies are not "fashionable", and thus grant money for this field is practically non-existent. Given the data collected to date and the worldwide suffering of millions of LFN-exposed citizens, this *status quo* situation is unethical, unsustainable, and downright obscene.

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Brain criticality emerges with developmental shifts in frequency-specific excitation-inhibition balance

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Abstract [characters (excluding spaces): 1794]

Adolescent brain maturation involves structural changes effecting a shift in excitation/inhibition (E/I) balance, yet the functional implications of these changes remain unclear. One implication is a shift with respect to criticality. Adult brains, at rest, operate near a critical phase transition – at the boundary between an active, excitation-dominant phase, and an absorbing, inhibition-dominant phase. Special properties emerge when neural systems are balanced at criticality, including maximal susceptibility to perturbation, dynamic range, and information transmission. Thus, a clear picture of how adolescent brain maturation affects E/I balance and criticality is needed to understand how maturational processes shape cognition. Here, we leverage the dynamical properties of longitudinally-collected resting-state EEG recordings during N = 310 sessions from 169 healthy human participants ranging in age from 10 to 33 years old to quantify E/I and proximity to criticality. We find that adult brains operate closer to criticality, including spectrally-widespread increases in long-range temporal correlations and amplitude bistability. We also find band-specific changes in excitation versus inhibition whereby the mechanisms driving low-frequency (θ to α) oscillations shift towards lower E/I–possibly because of increasing inhibition–while the mechanisms driving high-frequency (γ) oscillations shift towards higher E/I, possibly because of decreasing inhibition. Opening eyes shifts brains towards lower E/I, and these state-dependent shifts are larger in adults. We simulate developmental effects with a neural mass model of coupled excitatory and inhibitory neurons providing a parsimonious account of how changes in brain dynamics could arise as a function of changes in local connectivity of excitatory and inhibitory neurons. Results indicate developmental movement towards criticality, and greater adaptability to state-specific demands, through adolescence to adulthood, reflecting changes in E/I balance with implications for cognitive development.

Introduction

At rest, the healthy adult brain operates at a boundary between dynamical regimes [1]. On one side of this phase transition, neural systems are inhibition-dominant and, at the limit, non-responsive. On the other, neural systems are excitation-dominant and, at the limit, chaotic. When excitation and inhibition are balanced near a critical point, emergent dynamics are optimal for computation. They confer susceptibility [1–4] – the propensity for the system to respond to inputs – and scale-free activity – implying persistence of information [5,6] and maximal dynamic range [7,8]. Thus, excitation-inhibition (E/I) balance determines proximity to criticality and sets the stage for diverse cognitive capacities.

Adolescent brains go through numerous changes in cortical architecture including pruning of excitatory synapses, the maturation of inhibitory interneurons, and the expression of GABA receptors, all suggesting a shift in the balance of excitation to inhibition [9–12]. Evidence of a developmental shift in E/I includes a reduction in glutamate relative to GABA metabolites in dorsolateral prefrontal cortex, as measured by magnetic resonance spectroscopy [13,14]. Broader shifts in E/I are also evident in systematic changes in aperiodic power as measured by MEG and EEG [13,15–17]. Namely, with development, oscillatory power is lower (lower offset of a model fit to 1/f power spectra) and power is also reduced by a greater degree in low versus high frequency bands (shallower 1/f slope) in adults. Machine learning and artificial neural network models fit to spontaneous resting-state dynamics in fMRI data also converge on the conclusion that development is associated with widespread reductions in E/I, across the cortex [18,19]. Distinctions across cortical regions in these models furthermore indicate that the rate of change in E/I differs between higher-order association areas, and lower-order, sensorimotor cortex, implying a diversity in the effects of development on excitation versus inhibition across the brain. Interestingly, a developmental shift in E/I in the association cortices, in particular, is linked to IQ in children [20].

A shift in E/I across the brain implies systematic shifting with respect to criticality. Indeed, as adolescents age into adulthood, their brains appear to operate closer to a critical point. Long-range temporal correlations – reflecting persistence and the capacity for integration – are one emergent property of criticality that has been found to grow stronger with development [21]. Signal complexity is another emergent property that is greater at criticality and has also been found to increase from early childhood into adolescence [22]. While long-range temporal correlations and complexity are maximal in critical systems, they diminish under either sub-critical, inhibition-dominance, or super-critical, excitation-dominance [23]. Thus, while brains appear to operate closer to criticality with age, the regime in which youths' brains operate is not specified by these results. These patterns also do not reveal the direction (increases or decreases in E/I) with which brains shift during development. Finally, there is likely to be a diversity of developmental effects on brain criticality in specific circuits. Even if there is a systemic shift in E/I, whether specific circuits shift towards or away from criticality depends on whether they start in inhibition-dominant, or excitation-dominant regimes.

In this study, we analyze spontaneous brain dynamics in EEG recordings in a sample of 169 healthy human participants ranging in age from 10 to 33 years old assessed longitudinally at approximately 18 month intervals (for a total of 331 recordings) during eyes-closed and eyes-open rest. We derive indices of brain criticality including long-range temporal correlations and bistability, and indices of E/I derived from the dynamics and distributional properties of signal amplitude. Importantly, we compute these metrics spectrally, i.e. across frequency bands, to detect individual differences and age-related shifts in both E/I values and criticality by band [24]. We find that adolescent development is associated with systemic shifting towards criticality. We also find that this shift corresponds with a diversity of changes in E/I metrics in different frequency bands, suggesting a diversity of developmental effects on E/I in distinct brain systems. In a contrast of eyes-closed versus eyes-open rest, we find that opening one's eyes consistently shifts brains in the direction of stronger inhibition but that this positions some participants' brains closer to, and others farther away from criticality. We also find that the effect of eyes opening on critical dynamics is larger in adults than in children. Together these results suggest that adult brains both operate closer to criticality with eyes closed and shift more dynamically, with respect to criticality, as a function of processing demands. Finally, we use simulations of an artificial neural network model – which passes through criticality when excitation and inhibition are balanced – to show that we can recapitulate developmental effects on spontaneous EEG dynamics, in each canonical frequency band, by manipulating the relative connection density for excitatory versus inhibitory neurons.

Results

Spectrally-widespread strengthening of critical dynamics with age

To test the hypothesis that brains develop towards criticality from adolescence to adulthood, we tested for two emergent properties of a complex, dynamical system at a critical point: long-range temporal correlations, and bistability. Long-range temporal correlations (LRTC) arise in the brain because, when excitation and inhibition are in balance, the effect of a perturbation neither diverges chaotically due to over-excitation nor dies off due to over-inhibition [23]. Bistability arises because critical systems, by definition, operate at the boundary between functional regimes and, therefore, can exhibit properties of both regimes over time [25]. In EEG data, we quantify LRTC in terms of the persistence of fluctuations in band-limited amplitude, using detrended fluctuation analysis (DFA; [26,27] see Methods). Bistability is quantified in terms of the degree to which the amplitude distribution of an EEG trace is best modeled by two distinct modes (bistability, BiS [25,28]), indicating vacillations between dynamical phases, rather than a single mode, which would indicate a single dynamical phase.

As predicted, we find that both spectrally-widespread LRTC and BiS strengthen with age (Figure 1) indicating a developmental shift towards criticality. Mixed effects regressions including both eyes-open and eyes-closed conditions revealed a main effect of age on increases in DFA and BiS across nearly all frequency bands, except for γ where DFA and BiS decrease with age. For example, in the α band (averaged from 8.3–13.4 Hz) DFA exponents (β = .351, $p = 10^{-8}$) and BiS scores increase with age (β = .251, $p = 10^{-5}$). Conversely, in the γ band (27.6–57.6 Hz) both DFA (β = -.197, p = .00176) and BiS decrease (β = -.163, p = .00981). Here, to account for the apparently non-linear effects of Age, our models are fit to $-1/Age$ [29]. These patterns provide evidence that the mechanisms driving low (θ, α, and β) but not high-frequency oscillations (γ) operate closer to criticality with development.

We also find strong effects of opening eyes on indices of criticality in our mixed effects regression models which included random intercepts for subjects, along with fixed effects for Condition (eyes-open versus -closed) and the Age × Condition interaction as predictors. Both DFA and BiS in the α band dampen when eyes open (DFA: β = -.467, $p = 10^{-14}$; BiS: β = -.179, p = .00455) indicating that opening eyes shifts α-generating systems away from the critical point. In contrast, opening eyes strengthens DFA statistics in the γ band (DFA: β = .147, p = .0180; BiS: β = -.0739, p = .340). Finally, we note a significant Age × Condition interaction for DFA (in the α band only: β = -.302, $p = 10^{-7}$; this interaction was not significant in the γ band) suggesting that the effect of development on DFA in the α band is stronger when eyes are closed. At the sensor level, positive effects of Age on both DFA and BiS are widespread, showing up across the surface of the scalp. In contrast, the negative effects of Age on γ-band DFA are more spatially selective, showing up specifically in lateral and posterior electrodes (Figure 1D).

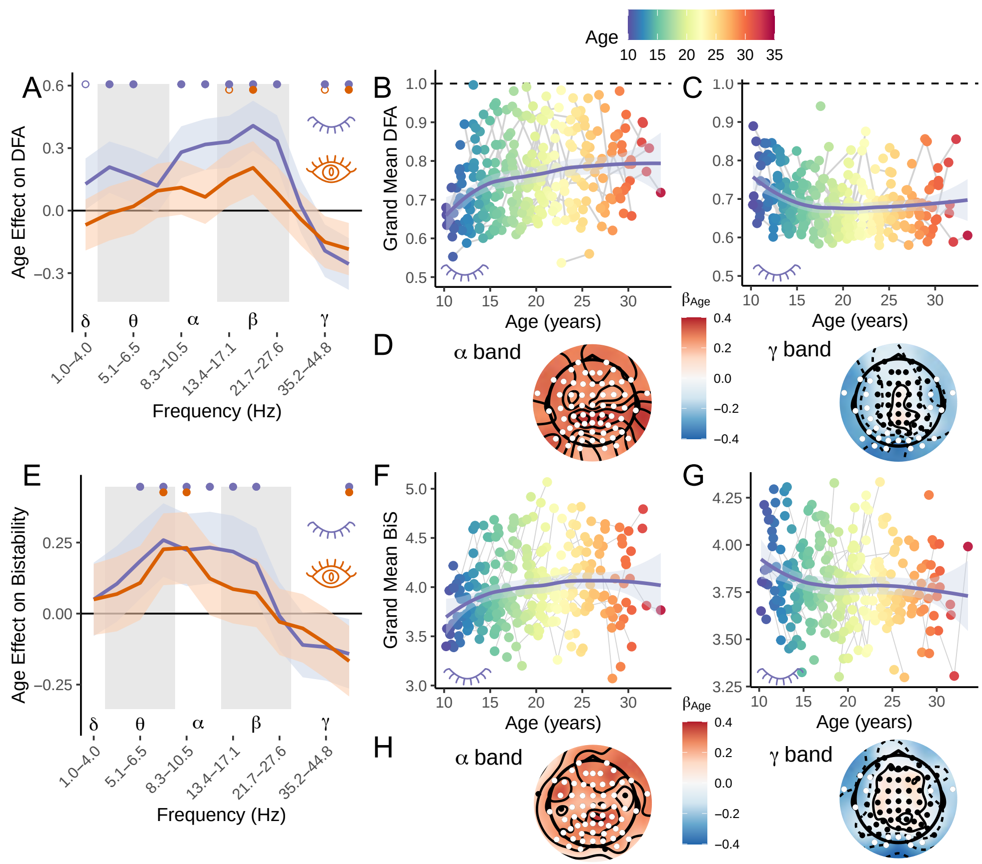

Figure 1 DFA exponents and BiS statistics show spectrally-widespread convergence towards criticality with development. A) Estimates of the fixed effect of age on mean, whole-brain DFA exponents for logarithmically spaced frequency bands from 1.0 – 57.6 Hz in mixed effects models with random intercepts for participants. Orange for eyes-open and purple for eyes-closed. Error bands indicate 95% CI. Closed dots indicate $p_{FDR} < .05$, with FDR correction for the number of frequency bands and open circles indicate uncorrected $p_{unc} < .05$. B,C) Mean, whole-brain DFA plotted as a function of age for the α band (8.3–13.4 Hz; left panel) and γ band (27.6–57.6 Hz, right panel). A dashed line indicates the theoretical expected value of a DFA exponents when the system operates at criticality (DFA = 1.0). Error bands indicate 95% CI. D) Corresponding, sensor-level correlations between age and DFA exponents in the α and γ bands. White circles indicate sensors where the effect of age was significant at $p < .01$. E) Estimates of the fixed effect of age on mean, whole-brain BiS estimates across frequency bands. F,G) Mean, whole-brain BiS estimates as a function of age in the α and γ bands. H) Corresponding, sensor-level correlations between age and BiS estimates in the α and γ bands.

Age-related changes in the excitation-inhibition ratio

Age-related increases in critical dynamics are consistent with the hypothesis that adolescent development systematically alters the ratio of excitation to inhibition (E/I) – a control parameter which determines proximity to criticality in the brain. The direction of a shift in E/I, however, is not unambiguous from changes in long-range temporal correlations or amplitude bistability, because they decrease when either excitation or inhibition dominate. To determine how development alters E/I, we examine three indices: the functional E/I index (fE/I [30]), which quantifies E/I in terms of correlations between signal amplitude and amplitude fluctuations (positive in subcritical regimes and negative in supercritical regimes), the high-to-low amplitude proportion (E/I_{HLP} [28]), which quantifies E/I in terms of the relative proportion of time in which system with bistable amplitude operates in a high-amplitude, excitation-dominant state versus a low-amplitude inhibition-dominant state, and the branching ratio (σ [31]) which evaluates the rate of growth of neuronal avalanches – or, in EEG data, high-amplitude bursts of neural activity clustered together in time. As E/I increases, avalanches grow faster, reflected in higher branching ratios.

The indices provide converging evidence for frequency-specific developmental effects, with decreasing E/I in mechanisms driving low-frequency oscillations and increasing E/I in the mechanisms driving high-frequency oscillations (Figure 2). Specifically, mixed effects models including Age, Condition and their interaction reveal that θ band (4.0–8.3 Hz) fE/I (β = -.223, p = 10^{-4}) and E/I_{HLP} scores decrease (β = -.243, p = 10^{-4}) with Age. Conversely, in the γ band (27.6–57.6 Hz) both fE/I (β = .261, p = 10^{-5}) and E/I_{HLP} increase (β = .220, p = 10^{-4}). Interestingly, this pattern suggests that development has a mix of effects on E/I across brain mechanisms associated with distinct frequency bands. There is also evidence of spatial heterogeneity in these patterns (Figure 2D,H).

The branching ratio (σ) quantifies a global index of the E/I ratio by computing the rate at which high-amplitude EEG bursts (“events”) lead to subsequent bursts, clustered together in time (“avalanches”) [32–35]. When excitation dominates, high amplitude bursts produce subsequent bursts at a higher rate, and the branching ratio is higher. We first observed that mean inter-event intervals decrease with development (Figure 2I). That is, high-amplitude bursts occur more frequently as individuals age. Branching ratio estimates depend strongly on the width of the bin used to discretize timeseries (the mean inter-event interval [32,33]), thus we controlled for mean inter-event-intervals when testing for an effect of Age on branching ratios. A mixed effect regression of branching ratio onto Age (β = .154, p = .00414) and Condition (β = -.217, p = 10^{-4}), correcting for inter-event-intervals reveals that branching ratios increase with Age (Figure 2J) and decrease, controlling for Age, when eyes open. Thus, with development, high-amplitude events occur more frequently and avalanches grow faster, indicating an increase in global E/I.

To further interpret individual differences in the branching ratio in terms of frequency-specific E/I, we regressed branching ratios onto fE/I, Condition and the fE/I × Condition interaction, in each of our frequency bands, separately. Because Age has effects on both fE/I and branching ratios, we included Age (as above, $-1/Age$) as a covariate. Our analyses reveal that higher E/I in the α, β, and γ range all predict higher global branching ratios, as expected (Figure 2K). Interestingly, higher fE/I values in the θ range predict lower branching ratios, suggesting that mechanisms which generate θ oscillations suppress high-amplitude EEG bursts.

These indices, considered together with long-range temporal correlations and bistability (Figure 1) reveal that mechanisms that generate low-frequency oscillations move closer to criticality via decreasing E/I, suggesting that low-frequency oscillatory systems move from super-critical to near-critical with development. In contrast, mechanisms which generate high-frequency (γ) oscillations show increasing E/I – helping to account for an increase in branching ratios. Although long-range temporal correlations and bistability are weaker in γ band activity, this does not necessarily imply that high-frequency oscillatory systems move away from criticality. Indeed, fE/I scores (Figure 2A,C) suggest that γ mechanisms begin in sub-critical states early in adolescence and move closer to criticality with development. Thus, developmental changes other than E/I ratios may account for the suppression of long-range temporal correlations and bistability in γ-generating mechanisms with age (see Discussion).

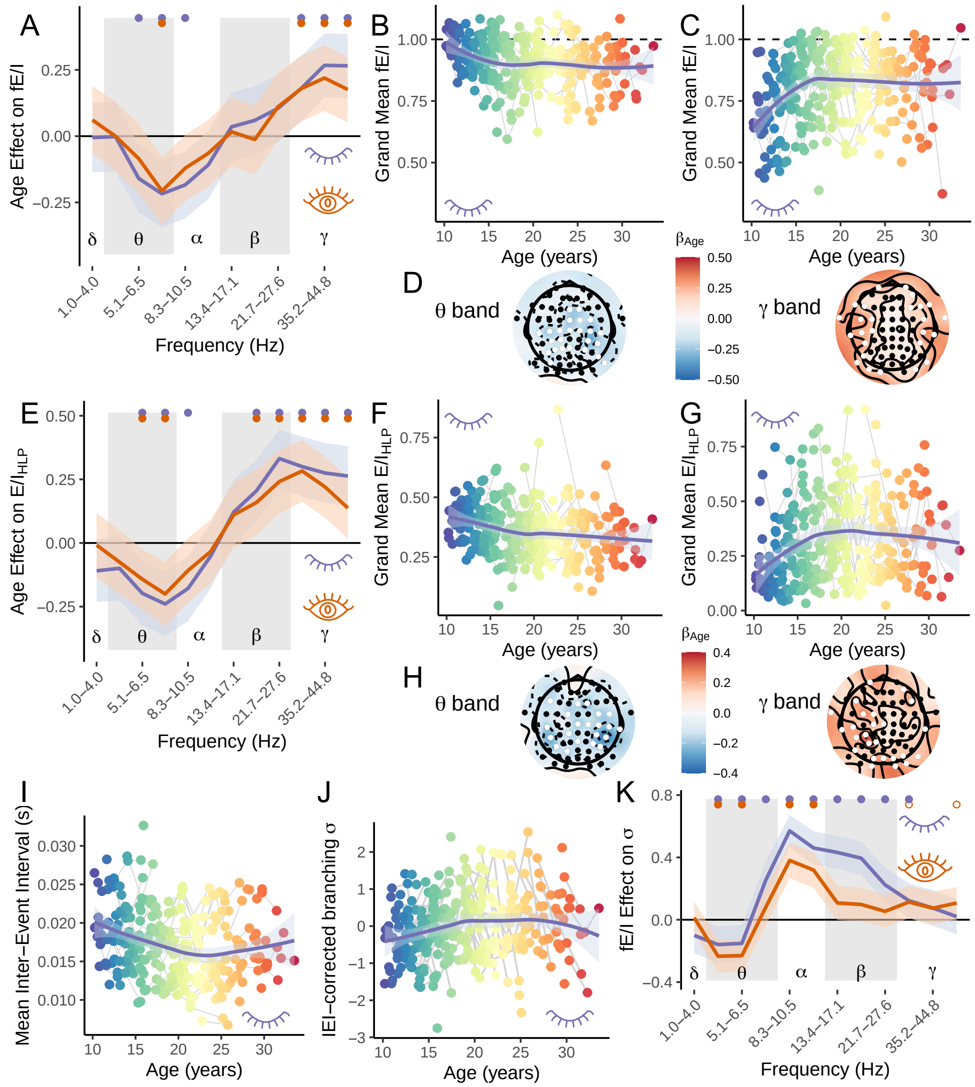

Figure 2 E/I indices fE/I and E/I$_{HLP}$ and the branching ratio all show spectrally-widespread changes with development. A) Estimates of the fixed effect of Age on mean, whole-brain fE/I exponents for logarithmically spaced frequency bands from 1.0–57.6 Hz in mixed effects models with random intercepts for participants. Orange for eyes-open and purple for eyes-closed. Error bands indicate 95% CI. Closed dots indicate p < .05, with FDR correction for the number of frequency bands and open circles indicate uncorrected p < .05. B,C) Mean, whole-brain fE/I plotted as a function of Age for the θ band (4.0–8.3 Hz; left panel) and γ band (27.6–57.6 Hz, right panel) with eyes closed. A dashed line indicates the theoretical expected value of fE/I exponents when operating at criticality (1.0). Error bands are 95% CI. D) Corresponding, sensor-level effect estimates for Age on fE/I in the θ and γ bands. White circles indicate sensors where the effect was significant at p < .01. E) Age effect estimates on mean, whole-brain E/I$_{HLP}$ across frequency bands. F,G) Mean, whole-brain E/I$_{HLP}$ as a function of Age in the θ and γ bands. H) Corresponding, sensor-level effect estimates for Age on E/I$_{HLP}$ in the θ and γ bands. I) Mean inter-event-intervals (IEI) in seconds decrease with Age. J) Controlling for IEIs, the branching ratio increases with Age. K) Estimates of the fixed effect of fE/I in each frequency band on branching ratio values, controlling for Age for both the eyes-closed and -open condition.

Age effects on excitation versus inhibition

While the previous analyses quantified the effects of development on the ratio of excitation to inhibition (E/I), we also leveraged orthogonal information provided by an index of combined excitatory and inhibitory strength (E+I) to make inferences more specifically about separable effects of development on excitation versus inhibition. Specifically, we calculated the high- and low-power separation index ($E+I_{HLS}$ [28]), which quantifies combined strength of excitation and inhibition in terms of the difference in power for high- and low-amplitude oscillations. The intuition behind this measure is that when both excitation and inhibition are strong, the swing between high and low amplitude dynamics is larger, as compared to when both are weak.

Mixed effects regressions of $E+I_{HLS}$ onto Age, Condition, and their interaction reveal increases with Age in low-frequency systems (θ, α, and β bands) and decreases with Age in the high-frequency γ range (Figure 3A–D). Thus, combined excitatory and inhibitory drive (E+I) strengthens with development in the mechanisms generating low frequency oscillations, while it attenuates in mechanisms generating γ oscillations. Taken together, information about E/I and E+I values, allow us to infer that inhibitory signaling must increase (or at least increase more than excitation), in low-frequency systems, to account for both a decrease in E/I and an increase in E+I, while it must decrease (more than excitation), in high-frequency systems, to account for both an increase in E/I and a decrease in E+I.

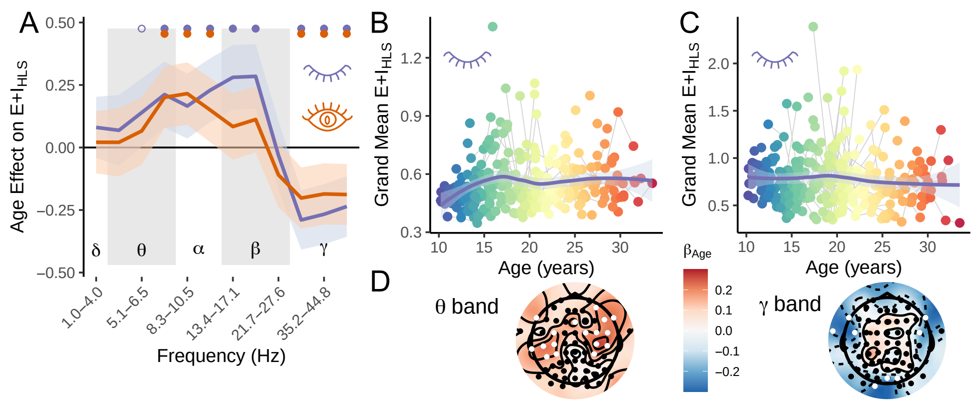

Figure 3 Age changes combined excitatory and inhibitory signaling as measured by the high-to-low power separation index ($E+I_{HLS}$) A) Fixed effect estimates of Age on mean, whole-brain $E+I_{HLS}$ for logarithmically spaced frequency bands from 1.0–57.6 Hz in mixed effects models with random intercepts for participants. Orange for eyes-open and purple for eyes-closed. Error bands indicate 95% CI. Closed dots indicate $p < .05$, with FDR correction for the number of frequency bands and open circles indicate uncorrected $p < .05$ B,C) Mean, whole-brain $E+I_{HLS}$ as a function of Age in the θ and γ bands in the eyes-closed condition. D) Corresponding, sensor-level effect estimates for Age on $E+I_{HLS}$ in the θ and γ bands. White circles indicate sensors where the effect was significant at $p < .01$.

Opening eyes shifts E/I ratios towards subcriticality

In general, correlations between age and markers of criticality and E/I are slightly, and at some frequencies significantly, stronger with eyes-closed than with eyes-open (Figure 1A,E & 2A,E). The direct effects of opening eyes on E/I and criticality indices, by contrast, are spectrally-widespread. Namely, when eyes are open, there is a systematic shift towards lower E/I (Figure 4C) and a suppression of long-range temporal correlations (Figure 4H), implying a shift to sub-criticality. Regarding E/I, opening eyes decreases branching rates σ ($t(283) = -10.4$, $p < 10^{-16}$; Figure 4B versus 4A), and also decreases, e.g., α band fE/I ($t(560) = -9.40$, $p < 10^{-16}$; 4A,B,C) and E/I_{HLP} ($t(297) = -8.72$, $p < 10^{-16}$), within individuals. The decrease in E/I is spectrally widespread, occurring at all frequencies except in the θ band (Figure 4C). The topography of the eyes opening effect on fE/I varies by frequency, with the effect being present across all channels in the α band but restricted to lateral and posterior sensors in the γ band (Figure 4E).

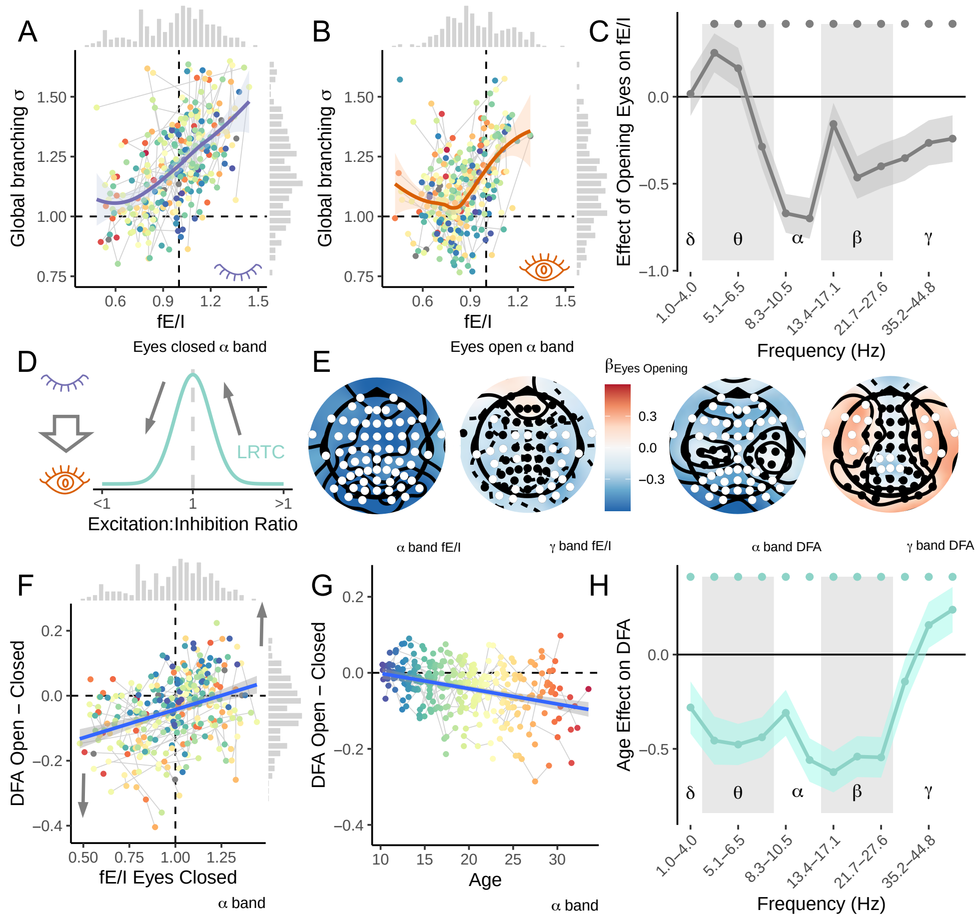

Figure 4 Opening eyes reduces E/I. A) Branching statistic σ correlates with fE/I for eyes closed resting data computed in the α band (8.3-13.4 Hz). Dashed lines indicate theoretical values of σ and fE/I at criticality. Grey bars show marginal histograms. B) Branching statistic σ correlates with fE/I for eyes-open resting data. C) The effect of opening eyes on mean fE/I scores across sensors from a mixed effects regression controlling for Age and the Age × Condition interaction. Solid dots indicate $p_{FDR} < .05$. D) Conceptual schematic of the effect of opening eyes anticipating a systematic shift towards lower E/I and thereby a shift towards criticality for supercritical brains, and a shift away from criticality for subcritical brains. E) Topography reflecting the effect of opening eyes on, from left to right, α band fE/I, γ band fE/I, and α and γ band DFA scores from a linear regression controlling for participant age and the age × eyes interaction. White sensors indicate $p < .01$. F) The difference in DFA estimates of long-range temporal correlations for eyes-open versus eyes-closed rest plotted against α band fE/I values at eyes-closed. Dark grey arrows show predictions for the difference score to the right and left of the critical value (fE/I = 1.0). G) The difference in DFA estimates for open versus closed eyes plotted as a function of age. H) The effect of opening eyes on mean DFA scores across sensors from a mixed effects regression controlling for Age and the Age × Condition interaction.

Because E/I controls proximity to criticality, the effect of eyes opening on fE/I also implies an effect on brain criticality. Indeed, opening eyes also results in spectrally-widespread decreases in DFA, e.g: in the α band (8.3-13.4 Hz; $t(298) = -7.37$, $p = 10^{-12}$). DFA decreases when eyes are open for all frequencies except the γ band, where long-range temporal correlations get stronger (27.6–57.6 Hz; $t(298) = 2.89$, $p = .00412$; Figure 3H). The topography of the effect of opening eyes on DFA also varies by frequency, with the effect being widespread across anterior and posterior channels, but not medial channels in the α band. In contrast, increases in γ-band DFA are focal on lateral-frontal sensors (Figure 3E). Interestingly, the effect of opening eyes is stronger with age. Controlling for the effect of fE/I on DFA values, we find a negative effect of Age (α band: $\beta = -.158$, $p = .0138$, Figure 3E; β band: $\beta = -.328$, $p = 10^{-7}$; all other bands $p \geq .382$) reflecting the fact that adults show a greater state dependence, relative to adolescents and children, with a bigger reduction in long-range temporal correlations when they open their eyes.

Although opening eyes decreases long-range temporal correlations for most frequencies at the group level (Figure 3G,H), the specific effect, at the level of the individual, should depend on E/I balance at baseline. Namely, brains operating in the subcritical regime when eyes are closed should shift away from criticality when eyes are opened, while brains operating the supercritical regime should shift towards criticality when eyes are opened (Figure 3D). Consistent with this prediction, we find that fE/I in the α band at eyes-closed rest correlates positively with the change in DFA exponents when eyes are opened ($\beta = .300$, $p = 10^{-7}$; Figure 3F). This finding confirms a core prediction about long-range temporal correlations as an emergent dynamical property when excitation and inhibition are balanced at criticality and fE/I as a valid measure of individual differences in the E/I control parameter with respect to a critical point.

Simulating developmental effects by frequency band

Developmental effects on E/I can be recapitulated by an artificial neural network [23,24,28], as a function of excitatory and inhibitory connectivity. The model comprises coupled excitatory and inhibitory neurons (Figure 5B) with varying degrees of local connection density (Figure 5A). Emergent dynamical properties indicate that the model undergoes a critical phase transition, when excitatory and inhibitory connectivity are balanced (black solid line, Figure 5C,D), including strong long range temporal correlations, power-law neuronal avalanches [23], and bistable amplitude distributions [24,28] (Supplemental Figure S1). Importantly, E/I_{HLP} and $E+I_{HLS}$ [28] increase along non-parallel vectors spanning the state space of possible models (Figure 5C,D), making it possible to project developmental trajectories.

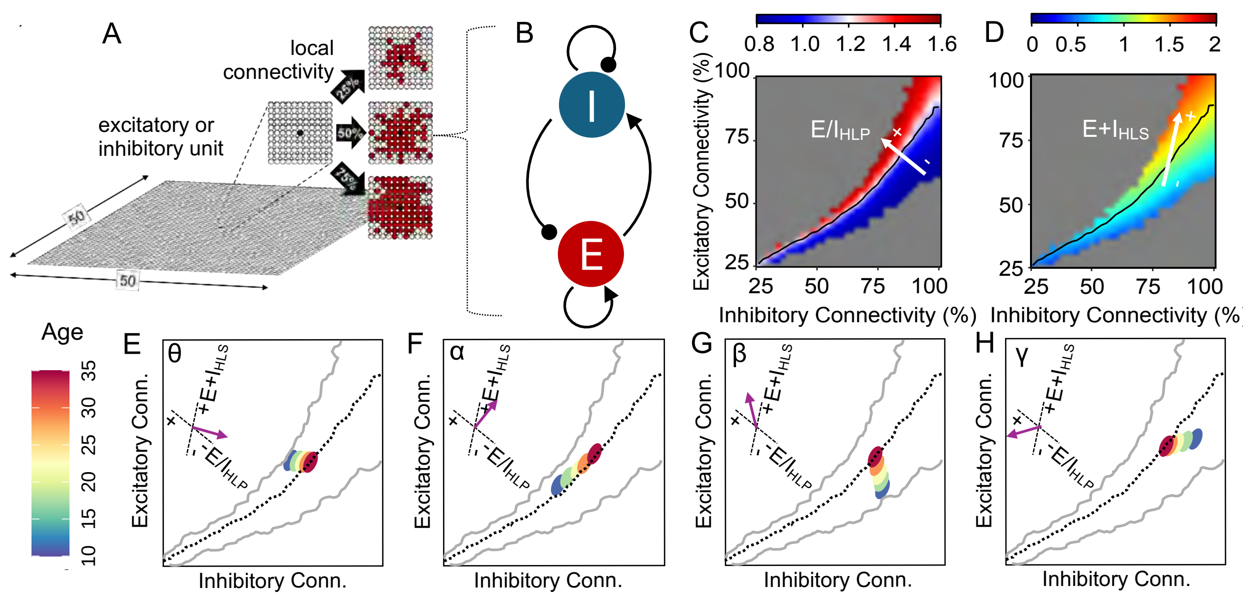

Figure 5 Simulations of an artificial neural network (introduced by [23], using parameters from [28]) recapitulating developmental effects on E/I balance and criticality. A) Network architecture includes coupled, recurrent excitatory and inhibitory units, in a large array (of 50 x 50 units) with local connection density as a model parameter. B) The circuit montage. C) E/I_{HLP} quantified from the amplitude distribution of summed network activity indicates a shift between high amplitude-dominant super-critical dynamics and low amplitude-dominant subcritical dynamics when excitation and inhibition are balanced at criticality, marked by a black line. Red-blue color scale indicates E/I_{HLP}. White arrow indicates the direction of the steepest gradient of increasing E/I_{HLP} in the phase space. C) $E{+}I_{HLS}$ quantified from summed network activity. Rainbow color scale indicates $E{+}I_{HLS}$. White arrow indicates increasing $E{+}I_{HLS}$ in the phase space. E-H) Feasible developmental trajectories (from ages 10, in red, to 35 in blue) across the phase space, for mechanisms driving θ, α, β, and γ oscillations based on E/I_{HLP}, $E{+}I_{HLS}$, and fE/I values. Inset shows the empirical direction of each trajectory, indicated by a purple arrow, based on empirical E/I_{HLP} and $E{+}I_{HLS}$ values.

We illustrate plausible developmental trajectories for mechanisms associated with each of the canonical frequency bands (θ, α, β, and γ), in terms of excitatory and inhibitory connection density (Figure 5E–H). The approximate position of the start (blue, Age = 10) and end (red, Age = 35) of each trajectory, relative to criticality (black dotted line) was determined by taking into account developmental changes in long-range temporal correlations and bistability (for determining proximity to criticality; c.f. Supplemental Figure S1), fE/I (for determining the sub- versus super-critical start and end points), and E/I_{HLP} and $E{+}I_{HLS}$ (for determining direction vector). The mean direction of each trajectory was determined based on developmental effects on E/I_{HLP} and $E{+}I_{HLS}$ values which span the state space [28]. While multiple mechanisms could effect an E/I shift, these simulations reveal that changes in excitatory and inhibitory connection density are sufficient to recapitulate developmental changes in spontaneous, resting EEG dynamics observed in our sample.

Discussion

Age-related changes in excitatory versus inhibitory signaling capacity suggest that the brain systematically shifts towards criticality, with development, from adolescence to adulthood. Consistent with this hypothesis, we replicate prior evidence that long-range temporal correlations grow stronger from adolescence into adulthood (Figure 1) [21]. We also find greater bistability in amplitude distributions. Furthermore, we find developmental effects across the frequency spectrum, but with variations by band. Namely, while markers of criticality become stronger in low-frequency bands (θ-through-β), they become weaker in the γ band.

Our findings also provide new insights into the changes driving shifts in critical dynamics. Namely, we find frequency-specific changes in functional E/I including decreases in excitation versus inhibition in the θ-through-α range and increases in high-β and γ according to complementary measures: fE/I and E/I_{HLP} (Figure 2). This developmental pattern converges with prior evidence of shallower slopes in the aperiodic spectrum with age, reflecting relatively higher power in fast versus slow oscillations [13,15–17]. Interestingly, we also find that branching ratios increase and that high amplitude bursts occur more frequently, suggesting an overall increase in the E/I ratio with development. Further analyses reveal that individual differences in branching ratios, controlling for age, correspond to higher E/I values in high frequency systems (α-through-γ) and lower E/I values in the θ band. Collectively, these results suggest a developmental increase in E/I in high-frequency systems and a developmental decrease in E/I in low-frequency systems, with consequences for the balance of spontaneous activity across the frequency spectrum.

Decreases in E/I indices for θ-through-α support the hypothesis that developmental pruning of excitatory synapses and maturation of inhibitory interneurons decreases the E/I ratio, especially in higher-order association areas [10,11,36]. Convergent evidence comes from analyses of prefrontal MR spectroscopy data showing decreased glutamate versus GABA metabolites with development [13,14]. Similar support comes from analyses of slow (fMRI BOLD) brain dynamics. For example, whole-brain simulations of reciprocally-connected excitatory and inhibitory populations best explain developmental changes in slow BOLD fluctuations in terms of decreasing E/I ratios, especially in higher-order association cortices [19]. Entirely different methods (machine learning-based inference) reveal that the effect of development on functional connectivity, especially in higher-order association areas, mimics the effect of a positive allosteric modulator increasing the efficacy of GABA-A receptors [18]. Thus, our results converge across a diversity of large-scale methods on the hypothesis that brain development through adolescence results in increased inhibitory versus excitatory drive in the mechanisms which generate and propagate θ and α oscillations.

Importantly, our results go beyond prior studies by suggesting not only a change in the E/I ratio, but separable effects on inhibition and excitation. Namely, considering effects on both E/I_{HLP} and $E{+}I_{HLS}$, we infer that development results in an increase in inhibitory signaling (at least relative to excitatory signaling) in mechanisms driving θ-through-α waves (Figures 2,3,5). A relative increase in inhibitory signaling is consistent with enhanced GABAergic transmission in prefrontal cortex driven by a developmental increase in long-range glutamatergic inputs to parvalbumin (PV)-positive, fast-spiking GABAergic interneurons [9,10] and the increased expression of GABA α1 receptors [12] . This developmental increase in glutamatergic inputs may increase inhibitory signaling by promoting interneuron activity directly, and by upregulating PV genes from adolescence into adulthood, resulting in a more sustained boost in GABAergic signaling capacity.

While E/I decreases in low frequency bands, it increases in high-β and γ. Because γ rhythms are determined principally by the time constants of GABA-A receptor-mediated inhibition [37], increases in E/I in higher frequency bands may also, paradoxically, reflect increased GABA-A signaling. Greater signaling capacity, especially at fast GABA α1 receptors, can potentiate γ oscillations in response to excitatory perturbations by amplifying the alternating dynamics in reciprocally-connected inhibitory interneurons, or reciprocally-connected excitatory and inhibitory interneurons [37]. One consequence of these developmental changes would be an increase in spontaneous γ power. Indeed, we find that both E/I indices which scale monotonically with mean amplitude (fE/I and E/I_{HLP}) increase with development in the γ band.

The combination of changes in critical dynamics and E/I imply that the systems driving specific frequencies shift differentially with respect to criticality. The strengthening of long-range temporal correlations and amplitude bistability in θ-through-β bands imply that these systems all shift towards criticality with development. In θ and α especially, the apparent decrease in E/I implies that these systems operate in a slightly super-critical regime in childhood and move towards criticality or even to a slightly sub-critical regime in adulthood. Conversely, the combination of weaker critical dynamics and an increase in E/I in the γ band for adults tells a different story. In terms of the fE/I index, γ oscillatory systems are sub-critical in children (fE/I $\ll$ 1.0) and approach criticality (fE/I = 1.0) in adulthood (Figure 2C).

If γ systems shift towards criticality, why, then, do emergent dynamics become weaker? It is important to note that emergent dynamics of a critical system – like long-range temporal correlations and bistability – reflect spontaneous, endogenous activity patterns that can be disrupted by external perturbation [38]. Inhibitory suppression by θ or α waves, for example, might halt on-going γ oscillations, thus blunting long-range temporal correlations. This interpretation is consistent with the hypothesis that low-frequency oscillations exert top-down control over high-frequency oscillations [39–42] and is supported by evidence of an increasing propensity for cross-frequency coupling (e.g. δ–γ coupling: [43] and α–β coupling: [44]) across adolescent development. Moreover, our own analyses of branching ratios as a function of band-specific fE/I also suggest that cross-frequency interactions impact on spontaneous, endogenous activity. Namely, we find that greater excitability in high-frequency systems is predictably associated with faster growing avalanches, but the opposite is true of greater excitability in the systems that generate θ-band activity. One interpretation is that when θ-generating systems are more excitable, they suppress spontaneous, high amplitude activity endogenous to high-frequency systems. Such interactions could thus blunt long-range temporal correlations and bistability in γ-band activity that would otherwise emerge at criticality.

In addition to developmental effects on E/I and critical dynamics, we also observe state-dependent changes in the contrast of eyes-closed and eyes-open conditions (Figure 4). Specifically, opening eyes decreases E/I indices including both decreased fE/I and branching statistics. Consistent with reduced broadband power when eyes open [42,45], we find decreases in E/I ratios for all frequencies except the θ band where opening eyes increases E/I. We speculate that decreases in E/I reflect an increase in feedforward and feedback inhibition, to stabilize processing of visual inputs [46,47] when eyes open. Such effects may also reflect functional re-configurations of E/I to accommodate attentional demands.

This state manipulation also offers an opportunity to test the hypothesis that emergent dynamics are strongest when excitation and inhibition are balanced at criticality [48]. Namely, if opening eyes shifts brains in a subcritical direction, then individuals with supercritical dynamics (fE/I > 1.0) should show stronger long-range temporal correlations when they open their eyes, while those with subcritical dynamics (fE/I < 1.0) should show weaker long-range temporal correlations when they open their eyes (Figure 4D). Our findings (Figure 4F) support this prediction while also, thereby, validating fE/I as an individual difference index of E/I balance, with respect to criticality.

The facts that slow oscillatory systems (frequencies below γ) tend to be subcritical, and that opening eyes decreases long-range temporal correlations for all slower frequencies (except θ; Figure 4H) implies that slow oscillatory systems become increasingly subcritical with the onset of visual input. Indeed, it is hypothesized that brains tend to operate in a slightly subcritical, inhibition-dominant regime to maximize responsiveness while also preventing runaway, chaotic dynamics in response to excitatory inputs [49,50]. Interestingly, the brain continues to shift in a subcritical direction as cognitive demands increase beyond perception to working memory, judgement, and decision-making tasks [47,51–53], suggesting that an adaptive shift towards subcriticality scales with cognitive load. Conversely, the strengthening of long-range temporal correlations in the γ band when eyes open, despite the concomitant decrease in fE/I, implies that some mechanisms other than shifting E/I balance must unblock emergent dynamics. Perhaps decreased power in slower frequency bands also decreases top-down, cross frequency coupling, thus freeing γ to more robustly express long-range temporal correlations. Given that γ waves are implicated in conveying bottom-up information [39,41,54], unblocking emergent dynamics when eyes are opened would be adaptive for visual perception, enhancing, e.g., susceptibility and dynamic range [2–8] for the perception of a diversity of visual stimuli. Finally, we find that state-dependent changes in critical dynamics are stronger in adults than in children. The change in α- and β-band long-range temporal correlations when opening eyes, for example, is robust for adults, but non-existent in the youngest participants (Figure 4G). Such patterns suggest the intriguing hypothesis that one outcome of development is an increased capacity for adults to shift brain criticality to adapt to state-dependent processing demands.

A key limitation of our work is the use of EEG which restricts spatially-resolved inferences about developmental effects. Nevertheless, the temporal resolution of EEG supports distinctions among mechanisms generating slow versus fast oscillations, and inhomogeneity in topographical effect maps further implies that developmental effects on brain criticality vary by brain region. Future work using MEG, MRI, and invasive neural recordings will be better positioned to assess the role of developmental effects across distinct brain regions.

Conclusion

Collectively, our results support the hypotheses that brains operate closer to criticality with development, and that this shift reflects mechanism-specific changes in E/I. We show that these developmental effects can also be evaluated in terms of emergent dynamics, as a function of neuronal oscillations, across frequency bands. Considering substantial evidence that criticality sets the stage for cognition by giving rise to emergent dynamics that support information processing, developmental shifts with respect to criticality have profound implications for cognitive function. Thus, our results motivate future studies examining how developmental shifts in emergent dynamics account for the enhancement of cognition across adolescent development and how brains adapt, across time, across state, and by mechanism, to accommodate to task demands.

Methods

Participants

N = 310 resting EEG recordings were collected from 164 healthy human participants (87/77 F/M) ranging in age from 10 to 33 years old at the University Pittsburgh Medical Center as part of a larger, longitudinal study characterizing developmental changes in signal processing supporting cognitive development. In an accelerated cohort design, participants each attended up to 3 visits, approximately 18 months apart. In addition to EEG and saccade task behavior, participants also completed a 7T MRI scan and a Spatial Span task (not analyzed here). Participants were recruited from the Greater Pittsburgh area and were excluded if they had a history of lost consciousness due to head injury, substance abuse, or major psychiatric or neurological condition in themselves or a first-degree relative, any learning disability, and non-correctable vision problems. All participants gave informed, written consent to participate or parents gave consent for those under 18 years old who provided assent. All experimental procedures followed an IRB-approved protocol, in compliance with the Declaration of Helsinki Code of Ethics of the World Medical Association.

EEG Recordings and Preprocessing

Participants were seated upright in a sound-attenuated, electromagnetically-shielded room for EEG recordings using a 64-channel cap with passive electrodes and a Biosemi ActiveTwo amplifier. 1024 Hz recordings were collected during interleaved eyes-open and eyes-closed rest (four, one-minute intervals of each) and down sampled to 512 Hz. Additionally, data were high-pass filtered at 1 Hz using a Hamming windowed sinc FIR filter (using the *pop_eegfiltnew* function in EEGLAB), bad channels were removed (*clean_artifacts*) and interpolated (*pop_interp*), data were re-referenced to the average (*pop_reref*), and finally ICA was used (*pop_runica*) to identify components which, according to the *ICLabel* algorithm, were likely to be muscle, eye, heart, line noise, or channel noise artifacts.

Measures of Brain Criticality and E/I Ratios

Emergent properties of a system at criticality include long-range temporal correlations, scale-free behavior, and multi-stability. We thus infer proximity to criticality from the strength of these properties.

Long-range temporal correlations refers to the propensity for the effects of a perturbation to persist longer than expected, e.g. by typical exponential decay. To measure *long-range temporal correlations* in EEG data, we use detrended fluctuation analysis (DFA) [26,27] to evaluate the persistence of amplitude fluctuations over time. Specifically, we extract the amplitude envelope via the Hilbert transform and take its cumulative sum over time. Next, the cumulative sum is broken up into windows of increasing duration. For each window size, the signal was broken into windows with 50% overlap, the linear trend is removed from each window, and the standard deviation of the detrended signal (referred to as the *fluctuation*) is computed. In systems with long-range correlations, this fluctuation function should grow rapidly as window durations increase. The rate of growth is quantified by the slope of a linear fit to a log-log plot of the mean fluctuation by window size. Higher slope values (closer to 1.0) indicate that the brain is operating closer to criticality [23].

Bistable dynamics arise when a system operates at the boundary of dynamical regimes because the system can express the dynamics of these distinct regimes over time without any further changes in control parameters. One clear example of bistability in EEG data is tendency of α waves to spontaneously transition between high and low amplitude oscillations over time [25]. The result of such transitions is that the amplitude distribution is better characterized by two modes rather than one. Here, following [28] we characterize bistability by the logarithm of the difference in the Bayesian Information Criteria scores for the fit of a bi-exponential versus a single exponential function to frequency-specific amplitude distributions. Higher values indicate that a bi-exponential model is an increasingly better description of the data and thus indexes criticality. First, we normalized the power time series (*P*) by its median value (converting *P* to *nP*), then we computed the probability density function by histogram (with 200 equally-spaced bins), and fit either a single, or bi-exponential function to the pdf using maximum likelihood estimation. The form of the single exponential model is

$$nP^x(x) = \gamma e^{-\gamma x} \tag{1}$$

and the bi-exponential is

$$nP^x(x) = \delta \gamma_1 e^{-\gamma_1 x} - (1-\delta)\gamma_2 e^{-\gamma_2 x} \tag{2}$$

where γ_1 and γ_2 are exponents and δ weights the prevalence of each exponential in the overall pdf. Finally, we computed the BIC scores for each fit, correcting for differences in signal length and computed bistability (BiS) as the logarithm of the difference in BIC scores between the exponential and bi-exponential model.

E/I can also be characterized with respect to emergent dynamics. For example, the functional excitation-inhibition index (or fE/I), was developed to capture the empirical relation between long-range temporal correlations and signal amplitude in the vicinity of criticality [30]. Namely, in the slightly subcritical domain when inhibition is dominant, long-range temporal correlations and amplitude correlate positively, and in the slightly supercritical domain when excitation is dominant, this correlation is negative. fE/I is computed as

$$fE/I = 1 - \rho_{nF,Amp} \tag{3}$$

where $\rho_{nF,Amp}$ is the Pearson correlation between the normalized fluctuation function (*nF*) and amplitude and thus takes on a value of 1.0 at criticality. Here, following [30] we first bandpass filter our signal, then extract the amplitude envelope via the Hilbert transformation. Next, we compute the cumulative sum of the amplitude envelope and segment it into 80% overlapping, 5 s windows. Windows are then normalized by the mean amplitude in each window. Next, the linear trend in each window is removed and the fluctuation function is computed as the root-mean square of the residuals. The mean, normalized fluctuation function and mean amplitude are then correlated across windows to calculate fE/I. Note that because fE/I is only meaningful in proximity to the critical point, we only calculate fE/I values when the corresponding DFA value for that EEG time course is greater than 0.6.

Spontaneous bursts of neuronal activity are referred to as avalanches [55], and the growth rate of these avalanches can be used to infer the balance of excitation to inhibition. In EEG data, the growth rate of avalanches can be indexed in terms of the growth of bursts of high amplitude signal, clustered together in time [33,34,56]. Following [31] we estimate the branching statistic (instantaneous growth rate) by the following steps. First, we identify high amplitude bursts (or "events") by thresholding EEG signal for each channel based on the point at which the amplitude distribution diverges from a best fit Gaussian model (2.5 SD in our data). Second, we discretize the timeseries by breaking into bins of width $\Delta\mathrm{t}$. Here we chose $\Delta\mathrm{t} = .8 * IEI$, approximating each individual participants' mean inter-event interval (IEI). We chose to use 80% of each participant's mean IEI because that bin width maximized the correlation between fE/I and branching statistics across participants (cf. Figure 4A). Of note, results remain the same if we use 100% of each participants' mean IEI or a fixed bin width across all participants (e.g. of 4 times the sampling rate, cf. [31]). Third, we identify avalanches as all events within contiguous time bins containing at least one event for any channel, separated by at least one time bin with no events. Fourth, we compute branching statistics as the ratio of the number of events in the second time bin of a given avalanche to the number of events in the first time-bin of a given avalanche. Finally, we compute a grand mean score by averaging branching statistics across all avalanches.

Another means of assessing E/I ratios in EEG data is to examine the ratio with which frequency-specific oscillations are high-amplitude versus low-amplitude, in a bistable system. Following [28] we use the fitted bi-exponential model parameter δ from Eqn. 4 which quantifies the weight of the pdf assigned to the high versus low power distribution in the bi-exponential model. This parameter, referred to as the proportion of high- to low-power oscillations index (E/I_{HLP}) has been shown to index the strength of recurrent excitatory versus inhibitory drive (the E/I ratio) in prior work simulating oscillatory dynamics with a neural mass model [28]. While E/I_{HLP} can, in principle, take values from $\delta = 0$ to 1, E/I_{HLP} is only interpretable in systems with bistable power dynamics. As such, we only compute E/I_{HLP} if BiS > 2.5 and only interpret values between 0.02 and 0.98 (c.f. Supplemental Figure S1).

Finally, we can also infer the combined strength of excitation and inhibition based on the separation between high- and low-power distributions. Indeed, for a given E/I ratio, the distance in amplitude separating the high- and low-power distribution grows as the sum of excitatory and inhibitory drive increases. Thus, the high-to-low-power separation index ($E+I_{HLS}$) was developed to quantify summed neurotransmitter capacity. Following [28] we calculate $E+I_{HLS}$ as the difference in the logarithm of the difference between the peak of the high-power exponential distribution and the peak of the low-power exponential distribution. As with E/I_{HLP}, we only compute $E+I_{HLS}$ if BiS > 2.5 and only interpret values of $E+I_{HLS}$ when E/I_{HLP} is between 0.02 and 0.98.

CROS Model Simulations

To simulate developmental effects on EEG dynamics, we adopted the CRitical OScillations model (from [23]), comprised of a 50 x 50 network of coupled, recurrent excitatory and inhibitory neurons that undergoes a critical phase transition as a function of the local connection densities of excitatory and inhibitory units. The CROS model generates oscillatory dynamics which evince criticality, including long-range temporal correlations and amplitude bistability when excitatory and inhibitory connectivity is balanced.

For our simulations, we used the same parameter set employed by Avramiea et al. (2025)[28], including 75% excitatory and 25% inhibitory neurons across our network, with excitatory and inhibitory connectivity ranging from 25% to 100% of neurons (in 2% steps across models) in a local grid of 7 x 7 neurons. 5 simulations for each combination of connectivity values were allowed to run for 1000 s. Net activity was calculated by summing up all spiking neurons at each time step, and adding in Gaussian white noise ($\mu = 0$; $\sigma = 3$) to induce time-varying phase, which otherwise does not occur during silent periods in the network. All analyses of E/I_{HLP}, and $E+I_{HLS}$ were performed on the amplitude of this summed signal, for each simulation, and statistics were averaged across the 5 simulations of each combination of excitatory and inhibitory connectivity values.

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The association between early-life respiratory infections and childhood asthma: a meta-analytic perspective

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Background: Early-life exposures and interventions establish essential pathways which determine children's development across respiratory, allergic, and growth pathways. The scientists conducted a systematic review and meta-analysis which combined multiple studies to examine how nutritional interventions and viral prophylaxis and probiotics and environmental exposures and allergen exposures and clinical factors in infants affect asthma and wheeze and atopy and growth outcomes.

Methods: The research team examined 51 studies which they categorized into eight different research areas. The researchers conducted random effects meta-analyses with inverse variance method to calculate pooled odds ratios (ORs) which included 95% confidence intervals (CIs). The researchers used I^2 statistics to measure heterogeneity while they used funnel plots and Egger's test to assess publication bias.

Results: The nutritional interventions during pregnancy (OR = 0.89, 95% CI: 0.74–1.07, I^2 = 68%) and early probiotics/microbiota modulation (OR = 1.10, 95% CI: 0.84–1.43, I^2 = 96%) failed to show any significant results. The combination of viral prophylaxis with maternal influenza vaccination protected against wheeze and asthma and LRTI development (OR = 0.78, 95% CI: 0.72–0.85, I^2 = 68%). The presence of early-life respiratory viral infections raised the likelihood of developing wheeze and asthma (OR = 1.59, 95% CI: 1.39–1.82, I^2 = 90%) which accompanied allergen/atopy exposures (OR = 1.40, 95% CI: 1.30–1.50) and environmental exposures (OR = 1.34, 95% CI: 1.27–1.42) and infant clinical factors (OR = 1.29, 95% CI: 1.13–1.46, I^2 = 82%). The long-term cohort studies established that early-life risk factors maintain a consistent impact on the development of asthma and allergic conditions (OR = 1.41, 95% CI: 1.35–1.48). The studies on viral prophylaxis and respiratory infections and allergen exposure demonstrated evidence of publication bias.

Conclusion: Research shows that early-life exposure to viral infections and allergens and environmental pollutants and infant clinical factors establishes strong links to the development of respiratory disorders and allergic diseases in children. The nutritional and probiotic treatments produced restricted and unstable results which demonstrate the requirement for specific preventive methods that should be implemented during early life.

KEYWORDS
childhood asthma, early-life respiratory infections, maternal vaccination, RSV prophylaxis, wheezing

1 Introduction

The early factors of respiratory susceptibility are getting more attention as childhood asthma remains a significant worldwide health concern (1–5). A large amount of epidemiological data suggests that the path toward asthma may begin in infancy, a time of development when the immunological and respiratory systems are more vulnerable to outside disturbances. Acute respiratory infections, especially those brought on by RSV, influenza, and other viral pathogens, have become prominent early-life exposures that can influence prolonged airway outcomes among these disruptions (6–9). Prophylactic trials have demonstrated that averting serious RSV illness in infancy lowers recurrent wheezing and hospitalization, making early-life RSV encounter one of the most frequently implicated viral determinants (10–12). In a similar vein, it has been demonstrated that maternal immunization can modify influenza-related respiratory morbidity in infancy, resulting in a considerable reduction in hospitalizations for respiratory tract infections and newborn influenza cases (13–15). The concept that early respiratory infections have significant downstream impacts on airway health and the occurrence of asthma is backed by all of these data.

Trials assessing perinatal nutritional modification offer further mechanistic knowledge. The idea that prenatal immunological programming affects postnatal respiratory consequences is supported by research showing that fish oil intake during pregnancy reduces chronic wheezing and asthma in children (16–19). Similar directionally positive impacts on early wheezing are shown by vitamin D trials, indicating that biological processes associated with infection susceptibility also intersect with asthma incidence (20–23). The interdependence of microbial exposures, immunological maturation, and atopic illness, all important components in asthma pathophysiology, is further highlighted by parallel data from early-life probiotic studies that show decreases in IgE-linked eczema and early atopic conditions (16, 17, 24–28).

Furthermore, studies focusing on airway physiology support the idea that early disruptions could affect subsequent respiratory traits. While high-intensity physical activity increases airway responsiveness in sedentary children (29–32), airway-hyperresponsiveness-guided asthma therapy enhances lung function metrics in school-age children (13–15, 18, 19). The basic foundation that unites these trials is that if early viral infection plays a role in the pathophysiology of asthma, then altering viral contact, infection intensity, or the host inflammatory milieu during initial stages might impact subsequent respiratory danger. Although individual trials provide valuable insights, overall interpretation is challenging due to variations in the nature, timing, magnitude, and outcome definitions. We compiled high-quality RCTs to investigate the potential link between early-life respiratory infections and subsequent wheezing and asthma in order to shed light on these trends. A variety of preventive measures targeted at altering early respiratory exposures are examined in this meta-analysis, which evaluates their cumulative connection with ongoing asthma-related consequences.

2 Methodology

2.1 Study design

This systematic review and meta-analysis were carefully designed and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) standards.

2.2 Search strategy

A thorough search was carried out using PubMed/MEDLINE, Scopus, Web of Science, Cochrane CENTRAL, and ClinicalTrials.gov from inception to December 2024. Search queries included controlled vocabulary (MeSH) and free-text terms such as: "early-life infection," "respiratory tract infection," "childhood asthma," "wheezing," "RSV prophylaxis," "maternal vaccination," "maternal supplementation," "vitamin D," "fish oil," "probiotics," "palivizumab," "exercise intervention,." Geographical or linguistic limitations were not imposed.

2.3 Eligibility criteria

Randomized controlled trials and observational studies that enrolled participants from prenatal to age 12 and assessed therapies that could change the timing, intensity, or tendency of early-life respiratory illnesses were eligible. Asthma, recurrent wheezing, respiratory hospitalization, atopic disease, or lung-function outcomes had to be reported in the trials, and they had to include extractable numerical data that could be used to calculate effect sizes using standardized mean differences. Studies that did not include early-life subjects, had limited outcome reporting, employed observational or quasi-experimental designs, or lacked a comparison group were disqualified.

2.4 Data extraction

A uniform template was used by a reviewer to extract data individually. Study design, sample size, intervention and control characteristics, geographic region, age at intervention or follow-up, respiratory infection type, severity characterization, definitions of asthma or wheeze outcomes, length of follow-up, and year of publication were among the variables that were obtained. To guarantee uniformity in stratified analyses, all retrieved variables were predefined. Conflicts were settled by dialog and agreement.

2.5 Quality assessment

The Cochrane RoB 2.0 tool was used to evaluate bias risk. The GRADE paradigm was used for rating the degree of certainty of the evidence, taking into account publication bias, indirectness, imprecision, risk of bias, and inconsistency.

2.6 Statistical analysis

A random-effects model with inverse-variance weighting was used to produce effect estimates. To account for discrepancies in outcome assessment between trials, OR and associated 95% confidence intervals were computed. To evaluate heterogeneity, the I2 statistic was employed. Age during infection or exposure, kind of respiratory illness, extent of infection, definition of asthma outcome, regional or socioeconomic context, length of follow-up, and publication time were all assessed in prespecified subgroup analyses. Publication bias was assessed via visual analysis of funnel plots. RevMan 5.4 was used for statistical analysis.

3 Results

3.1 Study selection

The overall systematic search process from one of the databases identified a total of several records, out of which 51 randomized controlled trials and clinical cohort studies were found to meet the appropriate criteria for inclusion and hence were the ones considered for this meta-analysis. One the other hand, studies reporting no relevant outcomes (asthma, wheezing, or atopic disease), non-randomized designs, or no suitable comparators were excluded from the analysis. Among others, the exclusion of certain studies comprised early observational studies on RSV without outcome reporting, small pilot trials lacking statistical power and studies outside the relevant age range (<1 month or >12 years). Figure 1 illustrates a flow diagram of the search, screening, eligibility, and inclusion process (Figure 1).

3.2 Characteristics of studies on early-life respiratory infections and childhood asthma

The studies that examine how respiratory infections during early life affect the development of asthma in children use both experimental research methods and observational research methods. The randomized controlled trials (RCTs) tested various interventions on pregnant women and preterm infants and high-risk children who received fish oil-derived n-3 fatty acids and vitamin D, probiotics, and palivizumab, motavizumab, and influenza vaccination. The study enrolled participants with sample sizes that ranged between 132 to 2,116 who received interventions starting from mid-pregnancy until their first year of life or during their seasonal RSV/influenza exposure. The study assessed four different outcomes, including persistent wheeze and asthma incidence and recurrent wheezing and allergic diseases. The observational studies, which included prospective and longitudinal and registry-based and population-based cohort studies, followed children from their birth until they

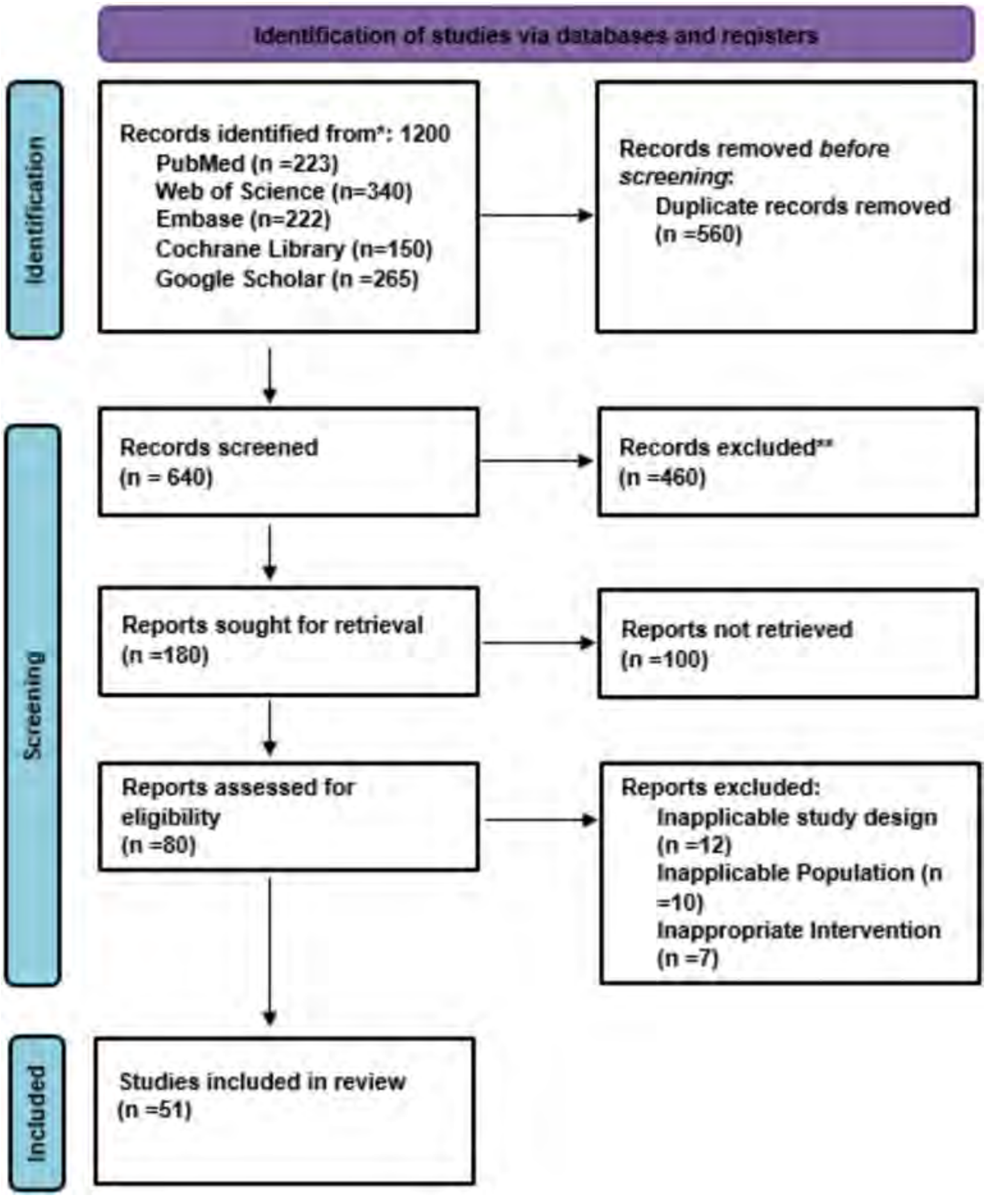

FIGURE 1
PRISMA flow chart of study selection.

reached adulthood, with study participants numbering between hundreds and more than 1 million. The research studies investigated how natural environments affect people through their respiratory infections and allergen exposure, antibiotic consumption, air pollution, and home environmental conditions. The evidence from both experimental studies and observational studies shows that early-life infections and environmental exposures result in increased asthma risk and allergic conditions that persist throughout childhood and later life (Table 1).

3.3 Certainty of evidence on early-life respiratory infections and childhood asthma

The evidence linking early-life respiratory infections to childhood asthma develops different levels of certainty across different research studies. The research findings achieve high certainty because the studies used randomized controlled trials which had minimal bias and generated exact results through their design. The studies show that maternal fish oil supplementation and RSV prophylaxis and influenza vaccination work as effective treatments which decrease wheeze and asthma and lower respiratory infections in infants. The research findings show moderate certainty because the trials used in the research contained indirect evidence and imprecise results according to the study outcomes. The research shows low to very low evidence between observational cohorts which include Shi et al. (1) and Nafstad et al. (33) because the research displays strong bias danger and potential publication bias. The research studies establish a relationship between early-life infections and environmental exposure which leads to higher asthma risk in patients (Table 2).

3.4 Risk of bias in studies on early-life respiratory infections and childhood asthma

The study's risk of bias evaluation shows both positive and negative aspects because it assesses research design strengths but fails to show complete study results and participant protection methods. The randomized controlled trials (RCTs), which include Bisgaard et al. (34), Roth et al. (35), Blanken et al. (36), Madhi et al. (37), Nunes et al. (38), Scheltema et al. (39), and Omer et al. (40) demonstrated that all study domains had a low risk of bias because the researchers presented all information and maintained participant and staff secrecy. The studies Litonjua et al. (41), Simoes et al. (42), and Feltes et al. (43) and multiple probiotic investigations displayed their doubtful risk assessment because of their main study elements, which included participant dropout rates, participant secrecy, and research results evaluation. Shi et al. (1) conducted observational studies, which demonstrated that the research design flaws generated high bias risks for selective reporting and other research areas, although the outcome assessment methods proved to be reliable. The studies display low to moderate bias which creates strong trust in early-life infection links to childhood asthma but shows the need for careful study interpretation (Figures 2A,B).

3.5 Group analysis

3.5.1 Group 1: nutritional interventions in pregnancy and offspring outcomes

The researchers studied three research projects that tested nutritional programs for pregnant women through their analysis of fish oil and vitamin D supplements. The researchers evaluated fish oil supplementation through their study, which examined its effects on asthma and wheeze development in children. The researchers studied vitamin D supplementation through two studies, which included Litonjua et al. (41) (VDAART) assessment of asthma and allergy results and Roth et al. (35) study of infant development. A meta-analysis using a random effects model with the inverse variance method was performed to compare odds ratios (ORs) across these studies. The pooled OR showed no statistically significant effect from prenatal nutritional interventions on the studied outcomes which produced a result of 0.89 (95% CI: 0.74–1.07). The researchers found significant heterogeneity between studies ($p = 0.04$; $I^2 = 68\%$), which showed that different studies produced different effects with different strengths. The researchers found that individual interventions produced different effects, but no evidence existed that showed these interventions produced major health benefits for children's respiratory development and growth progression (Figure 3).

3.5.2 Group 2: viral prophylaxis and vaccination in infants and pregnant women

The research team analyzed eight distinct studies that investigated viral prophylaxis and vaccination methods through their assessment of three specific areas which included RSV prophylaxis and influenza vaccination during pregnancy and point-of-care testing. The researchers tested three different types of RSV interventions, which included palivizumab (36, 42) and motavizumab versus palivizumab (43) and the general RSV prophylaxis (39) to evaluate their impact on recurrent wheezing and RSV disease, and asthma. The researchers investigated the impact of influenza vaccination through three studies, which included Madhi et al. (37), Nunes et al. (38), and Omer et al. (40) to determine its effect on protecting infants from lower respiratory tract infections, their ability to grow, and their need for hospitalization. The researchers studied antibiotic prescribing practices through point-of-care testing, according to the study conducted by Mattila et al. (44). The meta-analysis, which used a random effects model and inverse variance method, generated a pooled odds ratio (OR) of 0.78 (95% CI: 0.72–0.85), which demonstrated a statistically significant overall effect through a $p < 0.05$ result. The study identified three different treatment methods, which showed varying results because of high heterogeneity ($p < 0.01$; $I^2 = 68\%$) while the study found that viral prophylaxis and vaccination methods provided protective advantages (Figure 4).

3.5.3 Group 3: early probiotics, microbiota, and childhood allergic outcomes

The research examined six studies that focused on the impact of early-life probiotics and gut microbiota changes and antibiotics and home environment factors on the development of childhood allergic diseases. Probiotic interventions included Cabana et al. (45), Abrahamsson et al. (46), and Kalliomäki et al. (47), which treated eczema, IgE-related eczema, and atopic disease. The studies examined childhood asthma and allergic disease development through research on microbiota and metabolic processes (48), antibiotic consumption and its effect on gut microbiota (49), and home environment and lifestyle elements (50). The meta-analysis used a random effects model with the inverse variance method to determine a pooled odds ratio (OR) of 1.10 (95% CI: 0.84–1.43), which showed no

TABLE 1 Baseline characteristics of the included studies.

Author(s)	Year	Country	Study Type & Population	Sample Size	Duration	Outcome
Bisgaard et al. (79)	2016	Denmark	Randomized, double-blind, placebo-controlled trial; pregnant women	736	From week 24 of pregnancy until 1 week after birth	Reduced risk of persistent wheeze or asthma in offspring by age 3 years
Litonjua et al. (41)	2014	USA	Randomized, double-blind, placebo-controlled trial; pregnant women	876	From 10–18 weeks gestation until delivery	Designed to assess primary prevention of asthma and allergies in children; results pending at study design stage
Roth et al. (35)	2018	Bangladesh	Randomized, double-blind, placebo-controlled trial; pregnant and lactating women	1,300	From 17–24 weeks gestation through 26 weeks postpartum	No significant effect on infant growth at 1 year; vitamin D levels increased safely
Simoes et al. (42)	2007	Multicenter (Europe & USA)	Randomized, placebo-controlled trial; infants born preterm	1,502	Monthly injections during RSV season	Reduced RSV hospitalization and subsequent recurrent wheezing in high-risk infants
Blanken et al. (36)	2013	Netherlands	Randomized, double-blind, placebo-controlled trial; healthy preterm infants	429	During first RSV season	Significantly reduced recurrent wheeze through first year of life
Feltes et al. (43)	2011	Multicenter (USA & Canada)	Randomized, double-blind, active-controlled trial; children with congenital heart disease	1,287	RSV season (monthly injections)	Motavizumab non-inferior to Palivizumab for preventing serious RSV disease
Madhi et al. (37)	2014	South Africa	Randomized, placebo-controlled trial; pregnant women	2,116	From 20–36 weeks gestation until delivery	Reduced influenza illness in mothers and infants during first 6 months
Mattila et al. (44)	2022	Finland	Randomized clinical trial; children <18 years with respiratory infection	1,000	During acute illness visit	Reduced unnecessary antibiotic use in children
Nunes et al. (38)	2017	South Africa	Randomized, placebo-controlled trial; pregnant women	2,116	From 20–36 weeks gestation until delivery	Reduced all-cause lower respiratory tract infection hospitalizations in infants
Scheltema et al. (39)	2018	Netherlands	Randomized, double-blind, placebo-controlled trial; healthy preterm infants	429	During first RSV season	Reduced RSV infection; no clear long-term effect on asthma development
Cabana et al. (45)	2017	USA	Randomized, double-blind, placebo-controlled trial; infants	184	First 6 months of life	Reduced eczema risk; trend toward lower asthma incidence
Abrahamsson et al. (46)	2007	Sweden	Double-blind, randomized, placebo-controlled trial; infants	230	First 6 months of life	Reduced IgE-associated eczema development

(Continued)

TABLE 1 (Continued)

Author(s)	Year	Country	Study Type & Population	Sample Size	Duration	Outcome
Kalliomäki et al. (47)	2001	Finland	Randomized, placebo-controlled trial; infants	132	First 6 months of life	Reduced risk of atopic disease during early childhood
Shi et al. (1)	2020	Multicenter	Observational cohort; infants with RSV infection	2,500	Birth to 6 years	RSV-associated ALRI in early life linked to recurrent wheeze and asthma
Nafstad et al. (33)	2000	Norway	Prospective cohort; children	12,000	Birth to 7 years	Early respiratory infections associated with higher childhood asthma risk
Ramsey et al. (51)	2007	USA	Prospective cohort; children	650	Birth to 7 years	Early-life respiratory illnesses linked to asthma and atopy in childhood
Belachew et al. (52)	2023	Finland	Longitudinal cohort; birth to young adulthood	3,500	Birth to 25 years	Respiratory infections associated with increased asthma risk over lifespan
Stokholm et al. (53)	2014	Denmark	Registry-based cohort; children	65,000	Birth to 6 years	Maternal propensity for infections associated with higher childhood asthma risk
Bønnelykke et al. (24)	2015	Denmark	Prospective cohort; children	1,000	Birth to 7 years	Early-life respiratory infections increase asthma risk regardless of virus type
De Marco et al. (64)	2004	Europe	European cohort study; children and adults	5,200	Birth to adulthood	Early-life exposures influence incidence and remission of asthma
Rhodes et al. (68)	2001	Australia	Birth cohort; at-risk children	500	Birth to adulthood	Early-life risk factors linked to adult asthma development
Rosas-Salazar et al. (6)	2023	USA	Prospective birth cohort; infants	1,500	Birth to 6 years	RSV infection in infancy associated with higher asthma incidence in childhood
To et al. (80)	2020	Canada	Prospective cohort; children	4,000	Birth to 10 years	Early-life air pollution exposure linked to higher asthma, rhinitis, eczema incidence
Matheson et al. (66)	2011	Europe	Prospective cohort; children	8,000	Birth to 10 years	Early-life factors associated with increased rhinitis incidence
Örtqvist et al. (67)	2014	Sweden	Nationwide population-based cohort with sibling analysis	1,200,000	Birth to 10 years	Antibiotics in fetal/early life associated with higher childhood asthma risk
Stern et al. (61)	2008	USA	Longitudinal birth-cohort study; children	1,037	Birth to adulthood	Early wheezing and bronchial hyperresponsiveness predicted adult asthma
Grabenhenrich et al. (65)	2014	Germany	Birth cohort study; children	3,500	Birth to 20 years	Early-life determinants influenced asthma risk up to age 20

(Continued)

TABLE 1 (Continued)

Author(s)	Year	Country	Study Type & Population	Sample Size	Duration	Outcome
Kusel et al. (71)	2007	Australia	Birth cohort; children	263	Birth to 6 years	Early-life viral infections and atopy increase risk of persistent asthma
Torrent et al. (57)	2007	Spain	Prospective cohort; infants	1,000	Birth to 6 years	Early-life allergen exposure associated with atopy, asthma, and wheeze
McKeever et al. (72)	2002	UK	Birth cohort; children	14,000	Birth to 10 years	Early infections and antibiotic use linked to higher allergic disease risk
Jackson et al. (32)	2008	USA	Prospective cohort; high-risk infants	289	Birth to 6 years	Wheezing rhinovirus illnesses predicted asthma development in high-risk children
Salam et al. (73)	2004	USA	Prospective cohort; children	5,000	Birth to 10 years	Early-life environmental exposures linked to asthma development
Aguilera et al. (81)	2012	Spain	Prospective cohort; infants	2,000	Birth to 2 years	Early-life outdoor air pollution exposure associated with respiratory symptoms, ear infections, eczema
Sin et al. (82)	2004	Canada	Population-based cohort; children	1,200	Birth to 6 years	Lower birth weight associated with higher risk of childhood asthma
Gehring et al. (83)	2015	Netherlands	Population-based birth cohort; children	3,700	Birth to adolescence	Air pollution exposure associated with asthma and rhinoconjunctivitis
MacIntyre et al. (84)	2013	Europe	Analysis of 10 European birth cohorts (ESCAPE)	20,000	Birth to 5 years	Air pollution exposure associated with increased RTIs in early childhood
Karvonen et al. (55)	2009	Finland	Birth cohort; infants	3,100	Birth to 2 years	Moisture damage at home linked to respiratory symptoms and atopy
Arrieta et al. (48)	2015	Canada	Prospective cohort; infants	138	Birth to 5 years	Early microbial/metabolic alterations influenced risk of childhood asthma
Illi et al. (59)	2006	Germany	Birth cohort; children	1,314	Birth to 7 years	Early perennial allergen sensitization associated with chronic asthma
Chawes et al. (63)	2014	Denmark	COPSAC2000 birth cohort; infants	411	Birth to 7 years	Cord blood vitamin D deficiency linked to asthma, allergy, and eczema
Klopp et al. (62)	2017	Canada	Prospective birth cohort; infants	1,500	Birth to 6 years	Infant feeding mode influenced risk of childhood asthma
Lau et al. (58)	2000	Germany	Prospective birth cohort; children	405	Birth to 7 years	Early exposure to house-dust mite and cat allergens increased childhood asthma risk

(Continued)

TABLE 1 (Continued)

Author(s)	Year	Country	Study Type & Population	Sample Size	Duration	Outcome
Carroll et al. (60)	2009	USA	Prospective cohort; infants	1,503	Birth to 5 years	Severity of infant bronchiolitis correlated with higher early childhood asthma risk
Holt et al. (69)	2010	Australia	Prospective cohort; preschoolers	300	Birth to 5 years	Early immunologic and clinical markers predicted atopy and asthma risk
Bisgaard et al. (34)	2010	Denmark	Prospective birth cohort; children	411	Birth to 3 years	Bacteria and viruses associated with wheezy episodes in young children
Patrick et al. (49)	2020	Canada	Population-based and prospective cohort; children	10,000	Birth to 10 years	Decreasing antibiotic use linked to lower asthma incidence, mediated by gut microbiota
Kapszewicz et al. (50)	2022	Poland	Prospective birth cohort; inner-city children	500	Birth to 6 years	Home environment and lifestyle factors influenced asthma and allergic disease risk
Jackson et al. (54)	2012	USA	Prospective cohort; infants	285	Birth to 3 years	Allergic sensitization causally linked to rhinovirus-induced wheezing in early life
Roda et al. (56)	2011	France	Prospective birth cohort (PARIS); infants	1,500	Birth to 1 year	Formaldehyde exposure associated with increased lower respiratory infections in infants
Sigurdardottir et al. (70)	2021	Europe	EuroPrevall-iFAAM birth cohort; children	2,000	Birth to 8 years	Early-life risk factors associated with allergic multimorbidity at school age
Omer SB et al. (40)	2020	Multicenter	Randomized controlled trial	10,000	6 months postpartum	Maternal influenza vaccination was effective in reducing laboratory-confirmed influenza in mothers and infants

significant overall impact. The research revealed substantial study variation through the study results, which resulted in ($p < 0.01$; $I^2 = 96\%$), showing major variation between study results. The research demonstrates that separate interventions affect allergy risk, but early microbiota-related interventions do not provide definite protection or harm to participants (Figure 5).

3.5.4 Group 4: early-life respiratory viral and infection exposures

The research team investigated nine studies that focused on how early-life respiratory viral infections and viral exposures affected the development of wheezing, asthma, and atopy in children. The investigation examined multiple studies that investigated RSV-associated acute lower respiratory infections (1) and early respiratory infections and illnesses (33, 51) and respiratory infections from birth (52) and maternal infection propensity (53) and rhinovirus-induced wheezing or allergic sensitization (32, 54). The research team brought forward evidence about how early viral exposures affect health outcomes (6). The meta-analysis applied a random effects model with an inverse variance method, which resulted in a pooled odds ratio (OR) of 1.59 (95% CI: 1.39–1.82), which showed that early-life respiratory infections increased the risk for recurrent wheezing and asthma at a statistically significant level ($p < 0.05$). The study revealed high heterogeneity, which showed that effect sizes showed both different magnitudes and different directions of impact ($p < 0.01$; $I^2 = 90\%$). The results demonstrate that early respiratory viral exposures function as severe risk factors that lead to respiratory health problems in children (Figure 6).

3.5.5 Group 5: early-life environmental exposures and childhood respiratory outcomes

The research examined six studies that assessed early environmental exposures during early life to determine their impact on human health through their link to air pollution, indoor moisture damage, and formaldehyde exposure. The researchers To,

TABLE 2 GRADE Assessment table of the included studies.

Study	Risk of Bias	Inconsistency	Indirectness	Imprecision	Publication bias	Overall Certainty (GRADE)
Bisgaard et al. (34)	Low	Not serious	Not serious	Not serious	Undetected	High
Litonjua et al. (41)	Low	Not serious	Not serious	Serious	Undetected	Moderate
Roth et al. (35)	Low	Not serious	Not serious	Not serious	Undetected	High
Simoes et al. (42)	Moderate	Not serious	Not serious	Serious	Undetected	Moderate
Blanken et al. (36)	Low	Not serious	Not serious	Not serious	Undetected	High
Feltes et al. (43)	Moderate	Not serious	Serious	Serious	Undetected	Low
Madhi et al. (37)	Low	Not serious	Not serious	Not serious	Undetected	High
Mattila et al. (44)	Low	Not serious	Serious	Not serious	Undetected	Moderate
Nunes et al. (38)	Low	Not serious	Not serious	Not serious	Undetected	High
Scheltema et al. (39)	Low	Not serious	Not serious	Not serious	Undetected	High
Cabana et al. (45)	Moderate	Not serious	Not serious	Serious	Undetected	Moderate
Abrahamsson et al. (46)	Moderate	Not serious	Not serious	Serious	Undetected	Moderate
Kalliomäki et al. (47)	Moderate	Not serious	Not serious	Serious	Undetected	Moderate
Shi et al. (1)	Serious	Not serious	Not serious	Not serious	Possible	Low
Nafstad et al. (33)	Serious	Not serious	Not serious	Not serious	Possible	Low
Ramsey et al. (51)	Serious	Not serious	Not serious	Not serious	Possible	Low
Belachew et al. (52)	Serious	Not serious	Not serious	Not serious	Possible	Low
Stokholm et al. (53)	Serious	Not serious	Not serious	Not serious	Possible	Low
Bønnelykke et al. (24)	Serious	Not serious	Not serious	Not serious	Possible	Low
de Marco et al. (64)	Serious	Not serious	Not serious	Serious	Possible	Very Low
Rhodes et al. (68)	Serious	Not serious	Not serious	Serious	Possible	Very Low
Rosas-Salazar et al. (6)	Serious	Not serious	Not serious	Not serious	Possible	Low
To et al. (80)	Serious	Not serious	Not serious	Not serious	Possible	Low
Matheson et al. (66)	Serious	Not serious	Not serious	Not serious	Possible	Low
Örtqvist et al (67)	Moderate	Not serious	Not serious	Not serious	Possible	Moderate
Stern et al. (61)	Serious	Not serious	Not serious	Not serious	Possible	Low
Grabenhenrich et al. (65)	Serious	Not serious	Not serious	Not serious	Possible	Low
Kusel et al. (71)	Serious	Not serious	Not serious	Not serious	Possible	Low
Torrent et al. (57)	Serious	Not serious	Not serious	Serious	Possible	Very Low
McKeever et al. (72)	Serious	Not serious	Not serious	Serious	Possible	Very Low
Jackson et al. (32)	Serious	Not serious	Not serious	Not serious	Possible	Low
Salam et al. (73)	Serious	Not serious	Not serious	Not serious	Possible	Low
Aguilera et al. (81)	Serious	Not serious	Not serious	Not serious	Possible	Low
Sin et al. (82)	Serious	Not serious	Not serious	Not serious	Possible	Low
Gehring et al. (83)	Serious	Not serious	Not serious	Not serious	Possible	Low
MacIntyre et al. (84)	Serious	Not serious	Not serious	Not serious	Possible	Low
Karvonen et al. (55)	Serious	Not serious	Not serious	Not serious	Possible	Low
Arrieta et al. (48)	Serious	Not serious	Not serious	Serious	Possible	Very Low
Illi et al. (59)	Serious	Not serious	Not serious	Not serious	Possible	Low

(Continued)

TABLE 2 (Continued)

Study	Risk of Bias	Inconsistency	Indirectness	Imprecision	Publication bias	Overall Certainty (GRADE)
Chawes et al. (63)	Serious	Not serious	Not serious	Serious	Possible	Very Low
Klopp et al. (62)	Serious	Not serious	Not serious	Not serious	Possible	Low
Lau et al. (58)	Serious	Not serious	Not serious	Serious	Possible	Very Low
Carroll et al. (60)	Serious	Not serious	Not serious	Not serious	Possible	Low
Holt et al. (69)	Serious	Not serious	Not serious	Serious	Possible	Very Low
Bisgaard et al. (34)	Serious	Not serious	Not serious	Not serious	Possible	Low
Patrick et al. (49)	Serious	Not serious	Not serious	Not serious	Possible	Low
Kapszewicz et al. (50)	Serious	Not serious	Not serious	Serious	Possible	Very Low
Jackson et al. (54)	Serious	Not serious	Not serious	Not serious	Possible	Low
Roda et al. (56)	Serious	Not serious	Not serious	Serious	Possible	Very Low
Sigurdardottir et al. (70)	Serious	Not serious	Not serious	Not serious	Possible	Low
Omer et al. (40)	Low	Not serious	Not serious	Not serious	Undetected	High

and MacIntyre, Aguilera, and Gehring conducted their research study on both outdoor and indoor air pollution to study its effects on childhood asthma, rhinitis, eczema, and respiratory infections. The study by Karvonen et al. (55) examined how home moisture damage affected respiratory symptoms and atopy, while Roda et al. (56) investigated how formaldehyde exposure led to lower respiratory infections. The meta-analysis implemented a random effects model together with the inverse variance method to generate a combined odds ratio (OR), which showed a value of 1.34 (95% CI: 1.27–1.42) that reached statistical significance at ($p < 0.05$). The studies demonstrated high consistency because they produced similar effect sizes, which displayed identical directions of impact. The research results demonstrate that early environmental exposures through air pollutants and indoor hazards function as major risk factors that lead to negative respiratory and allergic effects in children (Figure 7).

3.5.6 Group 6: early-life allergen and atopy exposures

The analysis examined three studies that researched how early-life allergen exposure affects atopy development. Torrent et al. (57) studied how general early allergen exposure affects atopy and asthma and wheeze development, while Lau et al. (58) examined the impact of dust mites and cat allergens on childhood asthma, and Illi et al. (59) studied how perennial allergens cause asthma sensitization. The meta-analysis employed a random effects model and inverse variance method to calculate a pooled odds ratio of 1.40 (95% CI: 1.30–1.50), which showed a significant link between early allergen exposure and higher asthma, wheeze, and atopy development risk ($p < 0.05$). The studies showed minimal heterogeneity because all studies produced similar effect sizes with identical directional outcomes. The research results demonstrate that early life allergen exposure creates a consistent risk for children to develop both atopy and respiratory allergies, which supports the need for environmental allergen control in high-risk groups (Figure 8).

3.5.7 Group 7: infant and early-life clinical factors

The research team conducted a study that involved six research studies which examined how infant clinical characteristics and early-life medical conditions affect the likelihood of developing asthma and allergy and eczema conditions during childhood and adulthood. Carroll et al. (60) examined how severe infant bronchiolitis cases affected the likelihood of developing asthma during early childhood while Stern et al. (61) investigated the connection between early wheezing episodes and bronchial hyper-responsiveness to adult asthma. Klopp et al. (62) studied different infant feeding methods, while Chawes et al. (63) studied how cord blood vitamin D deficiency affects the development of asthma and allergy and eczema conditions. The researchers applied a random effects model with inverse variance method to conduct their meta-analysis which resulted in a pooled odds ratio (OR) of 1.29 (95% CI: 1.13–1.46) that showed a statistically significant overall effect ($p < 0.05$). The researchers found that the studies showed high heterogeneity because their results differed in magnitude and direction ($p < 0.01$; $I^2 = 82\%$). The results of this research study established essential clinical risk factors from early human development which predict respiratory and allergic disorders that will occur in the future (Figure 9).

3.5.8 Group 8: early-life cohort and long-term observational studies

Eleven studies examining early-life determinants and long-term observational outcomes were analyzed to assess risk factors for asthma, atopy, and allergic diseases. These studies included assessments of early-life exposures (64–67), early-life risk factors (68–70), early viral infections and atopy (71), early infections and antibiotic exposure (72), environmental exposures (73), and bacterial/viral influences (48). The research measured four outcomes, which included asthma incidence and remission and wheezy episodes and the development of multiple allergic conditions. The random effects model meta-analysis with inverse variance method

Study	D1	D2	D3	D4	D5
Bisgaard et al., 2016	+	+	+	+	+
Litonjua et al., 2014	+	+	+	+	+
Roth et al., 2018	+	+	+	+	+
Simoes et al., 2007	?	+	+	+	+
Blanken et al., 2013	+	+	+	+	+
Feltes et al., 2011	+	+	+	+	+
Madhi et al., 2014	+	+	+	+	+
Mattila et al., 2022	+	+	+	+	+
Nunes et al., 2017	+	?	+	+	+
Scheltema et al., 2018	+	+	+	+	+
Cabana et al., 2017	+	+	+	+	+
Abrahamsson et al., 2007	+	+	+	+	+
Kalliomäki et al., 2001	+	+	+	+	+
Shi et al., 2020	−	−	+	+	+
Nafstad et al., 2000	+	+	+	+	+
Ramsey et al., 2007	+	+	+	+	+
Belachew et al., 2023	+	+	+	+	+
Stokholm et al., 2014	+	?	+	+	+
Bønnelykke et al., 2015	+	+	+	+	+
de Marco et al., 2004	+	+	+	+	+
Rhodes et al., 2001	+	+	+	+	+
Rosas-Salazar et al., 2023	+	?	+	+	+
To et al., 2020	+	+	+	+	+
Matheson et al., 2011	+	+	+	+	+
Örtqvist et al., 2014	+	+	+	+	+
Stern et al., 2008	+	+	+	+	+

Study	D1	D2	D3	D4	D5
Grabenhenrich et al., 2014	+	?	+	+	+
Kusel et al., 2007	+	+	+	+	+
Torrent et al., 2007	+	+	?	+	+
McKeever et al., 2002	+	?	+	+	+
Jackson et al., 2008	+	+	+	+	+
Salam et al., 2004	+	+	+	+	+
Aguilera et al., 2012	+	+	+	+	+
Sin et al., 2004	+	+	+	+	+
Gehring et al., 2015	+	+	+	+	+
MacIntyre et al., 2013	+	+	+	+	+
Karvonen et al., 2009	+	?	?	+	+
Arrieta et al., 2015	+	+	+	+	+
Illi et al., 2006	+	+	+	+	+
Chawes et al., 2014	+	−	+	+	+
Klopp et al., 2017	+	+	+	+	+
Lau et al., 2000	+	+	−	+	+
Carroll et al., 2009	+	+	+	+	+
Holt et al., 2010	+	?	+	+	+
Bisgaard et al., 2010	+	?	+	+	+
Patrick et al., 2020	+	+	+	+	+
Kapszewicz et al., 2022	+	?	+	+	+
Jackson et al., 2012	+	+	+	+	+
Roda et al., 2011	+	?	+	+	+
Sigurdardottir et al., 2021	+	+	+	+	+
Omer et al., 2020	+	+	+	+	+

FIGURE 2 (Continued)

produced a pooled odds ratio (OR) of 1.41 (95% CI: 1.35–1.48), which established a significant overall effect ($p < 0.05$). The studies demonstrated low heterogeneity, which produced consistent effect sizes that appeared in all research conducted. The research results demonstrate that early-life factors have a major effect on how respiratory and allergic conditions develop throughout life (Figure 10).

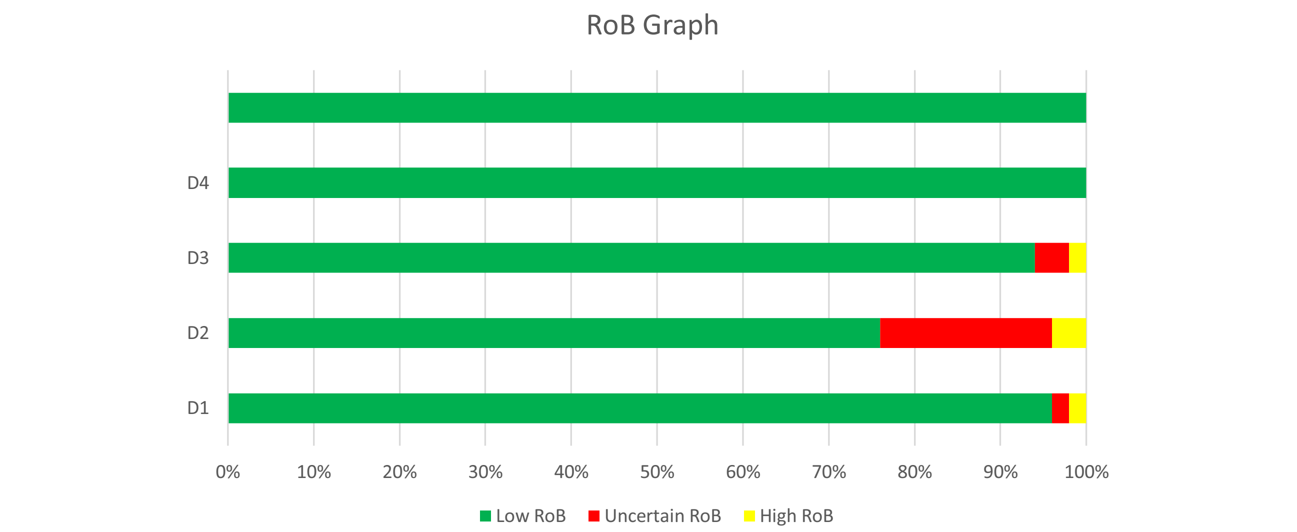

FIGURE 2
(A) Risk of bias (RoB) table of the included studies, D1 – Other, D2 – Selective reporting, D3 – Incomplete outcome (attrition), D4 – Blinding of outcome assessment, D5 – Blinding participants/personnel. **(B)** Risk of bias graph, D1 – Other, D2 – Selective reporting, D3 – Incomplete outcome (attrition), D4 – Blinding of outcome assessment, D5 – Blinding participants/personnel.

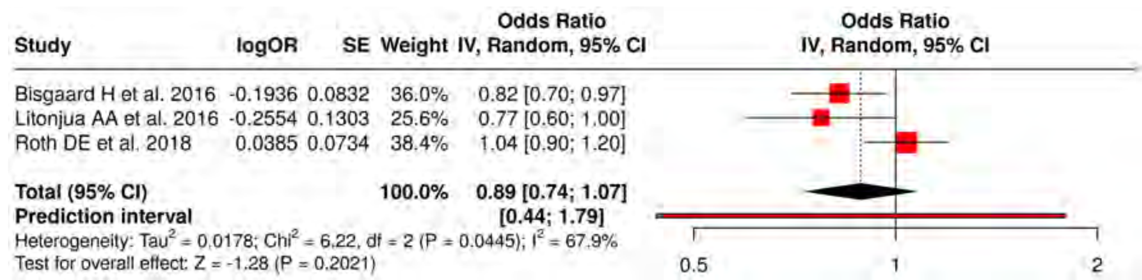

FIGURE 3
Forest plot of studies about nutritional interventions in pregnancy and offspring outcomes.

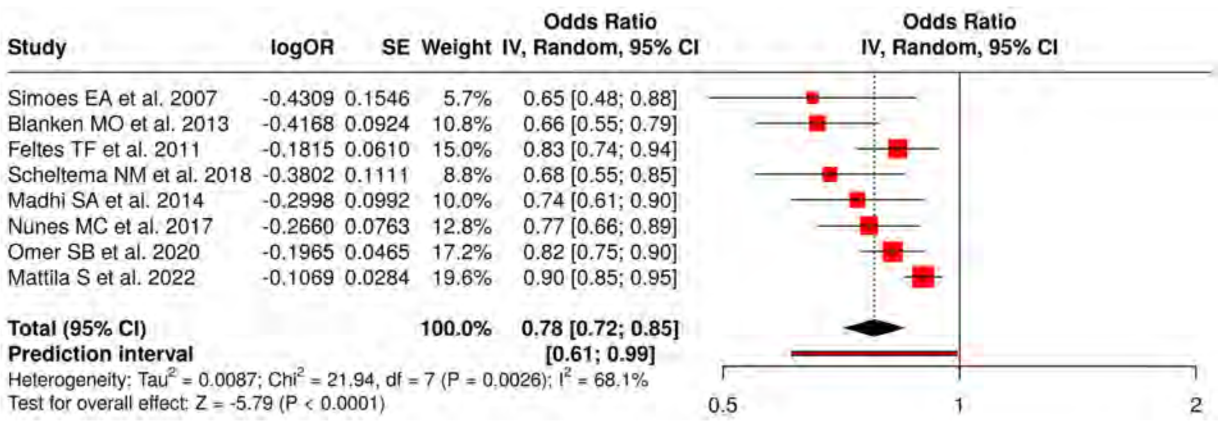

FIGURE 4
Forest plot of studies about viral prophylaxis and vaccination in infants and pregnant women.

3.6 Publication bias assessment

Research on publication bias assessment showed eight different categories of early-life interventions and exposures through the use of funnel plots and Egger's test. The funnel plot for Nutritional Interventions in Pregnancy showed no signs of bias, which Egger's test confirmed with an intercept value of −4.73 and a 95% confidence interval from −13.54 to 4.09, and a t-value of −1.051 and a *p*-value of 0.484. The research found no publication bias through the analysis of Early Probiotics and Microbiota with an intercept value of 8.35 and a 95% confidence interval from −8.3 to 25.01, and a t-value of 0.983 and a *p*-value of 0.381. The analysis of Early-Life Environmental Exposures with an intercept value of −4.55 and a 95% confidence interval from −10.94 to 1.84, and a *t*-value of −1.396 and a *p*-value of 0.235. The analysis of Infant and Early-Life Clinical

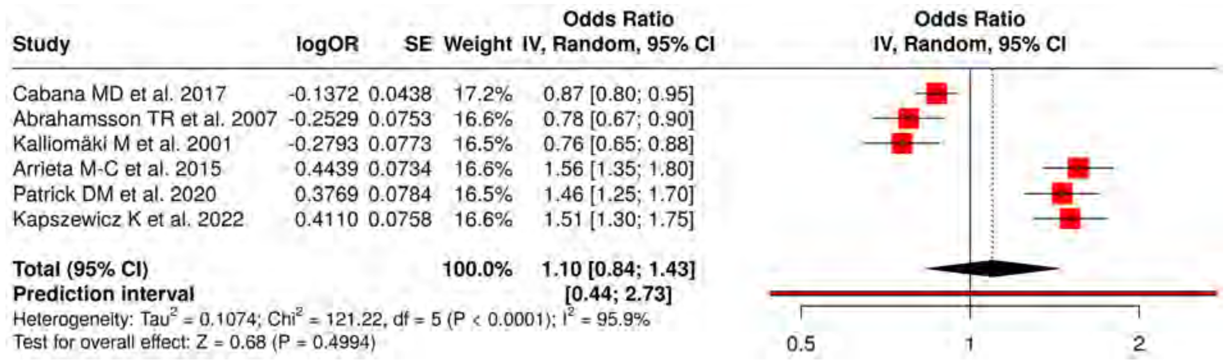

FIGURE 5
Forest plot of studies about early probiotics, microbiota, and childhood allergic outcomes.

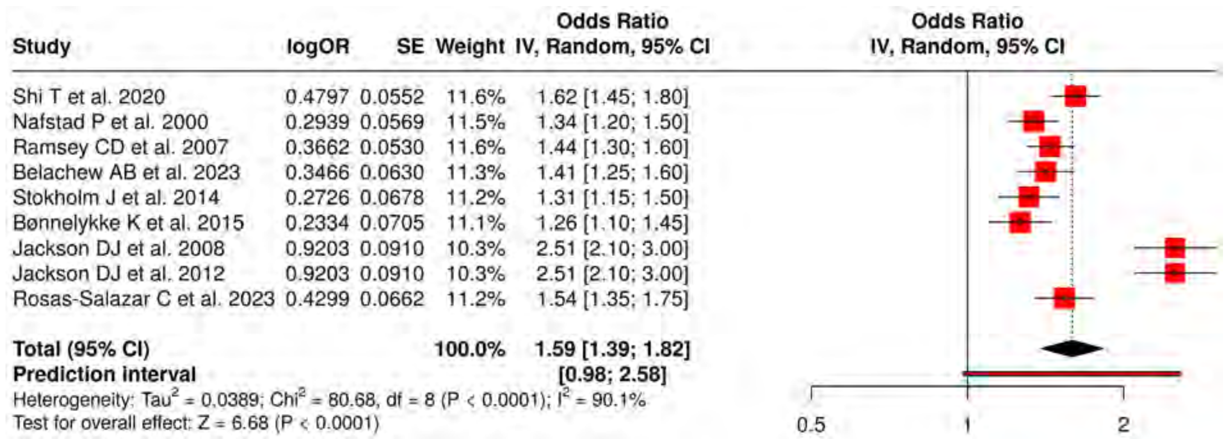

FIGURE 6
Forest plot of studies about early-life respiratory viral and infection exposures.

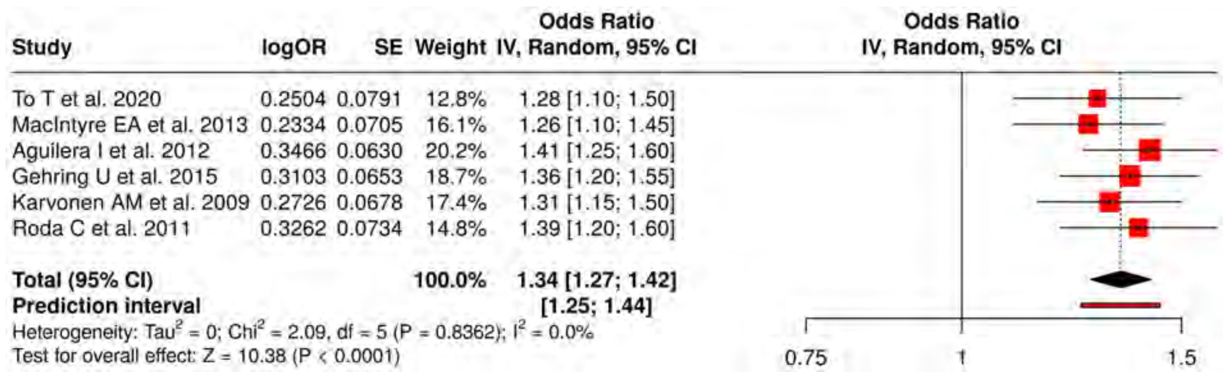

FIGURE 7
Forest plot of studies about early-life environmental exposures and childhood respiratory outcomes.

Factors with an intercept value of 25.18 and a 95% confidence interval from −23.98 to 74.33, a t-value of 1.004, and a *p*-value of 0.372. The analysis of Early-Life Cohort and Long-Term Observational Studies with an intercept value of 2.83 and a 95% confidence interval from −4.7 to 10.37, a t-value of 0.737, and a *p*-value of 0.48. The research showed three tests, which showed publication bias, including Viral Prophylaxis/Vaccination, whose results have an intercept value of −3.17, a confidence interval between −4.04 to −2.30, a t-value of −7.138, and a *p*-value of zero. Early-Life Respiratory Viral/Infection Exposures whose results have an intercept value of 11.83 and a confidence interval between 2.6 to 21.06 and a t-value of 2.513, and a p-value of 0.04. Early-Life Allergen/Atopy Exposures whose results have an intercept value of −15.68 and a confidence interval which includes only the value −15.68, a t-value of -1.08×10^{14} and a *p*-value of zero. The research results showed strong analysis results except for three categories, which displayed asymmetric patterns (Figure 11).

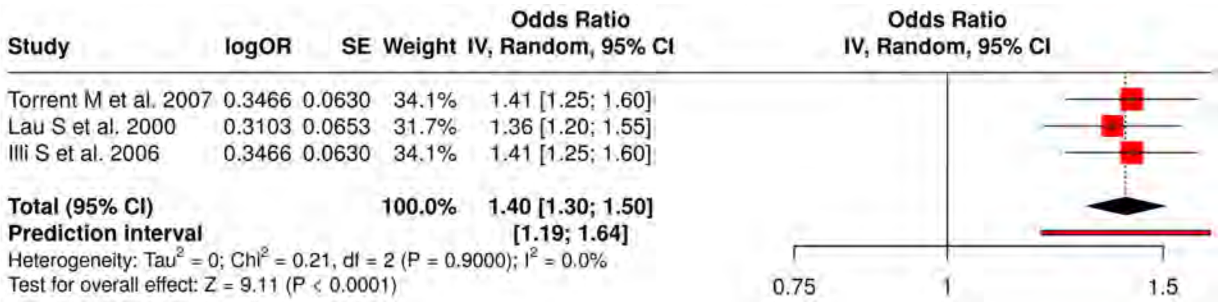

FIGURE 8
Forest plot of studies about early-life allergen and atopy exposures.

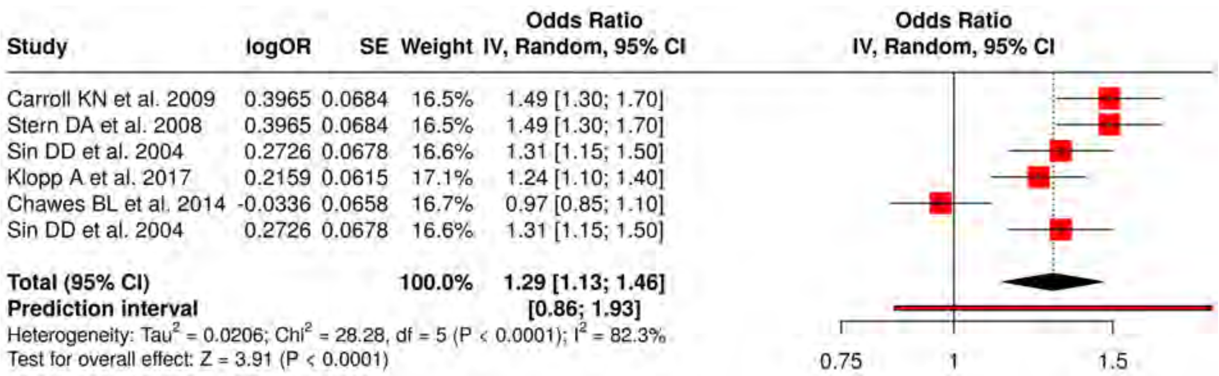

FIGURE 9
Forest plot of studies about infant and early-life clinical factors.

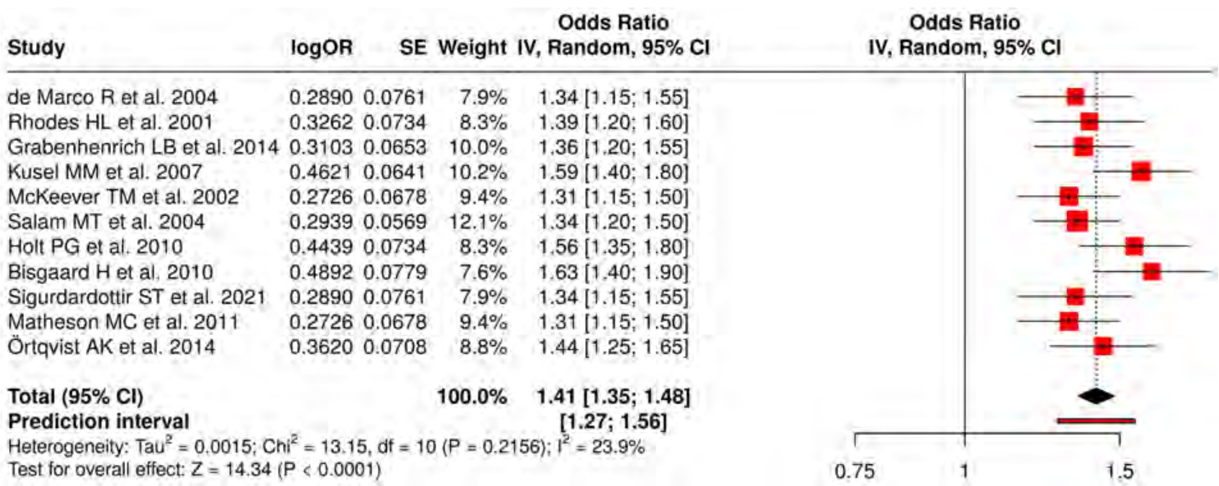

FIGURE 10
Forest plot of studies about early-life cohort and long-term observational studies.

4 Discussion

4.1 Summary of main findings

The investigation included 62 studies that examined eight types of early-life interventions and exposures to determine their effect on respiratory disorders, allergic reactions, and physical development in children. The dietary interventions tested during pregnancy, which included fish oil and vitamin D, proved to have no measurable effect on the development of wheeze and asthma and growth among offspring (pooled OR = 0.89, 95% CI: 0.74–1.07), which showed considerable variation (I^2 = 68%). The combination of viral prophylaxis with maternal vaccination reduced the chances of developing recurrent wheeze, asthma, and lower respiratory tract infections (OR = 0.78, 95% CI: 0.72–0.85; I^2 = 68%). The use of early probiotics together with microbiota modulation methods produced no meaningful impact on atopy or asthma development (OR = 1.10, 95% CI: 0.84–1.43; I^2 = 96%).

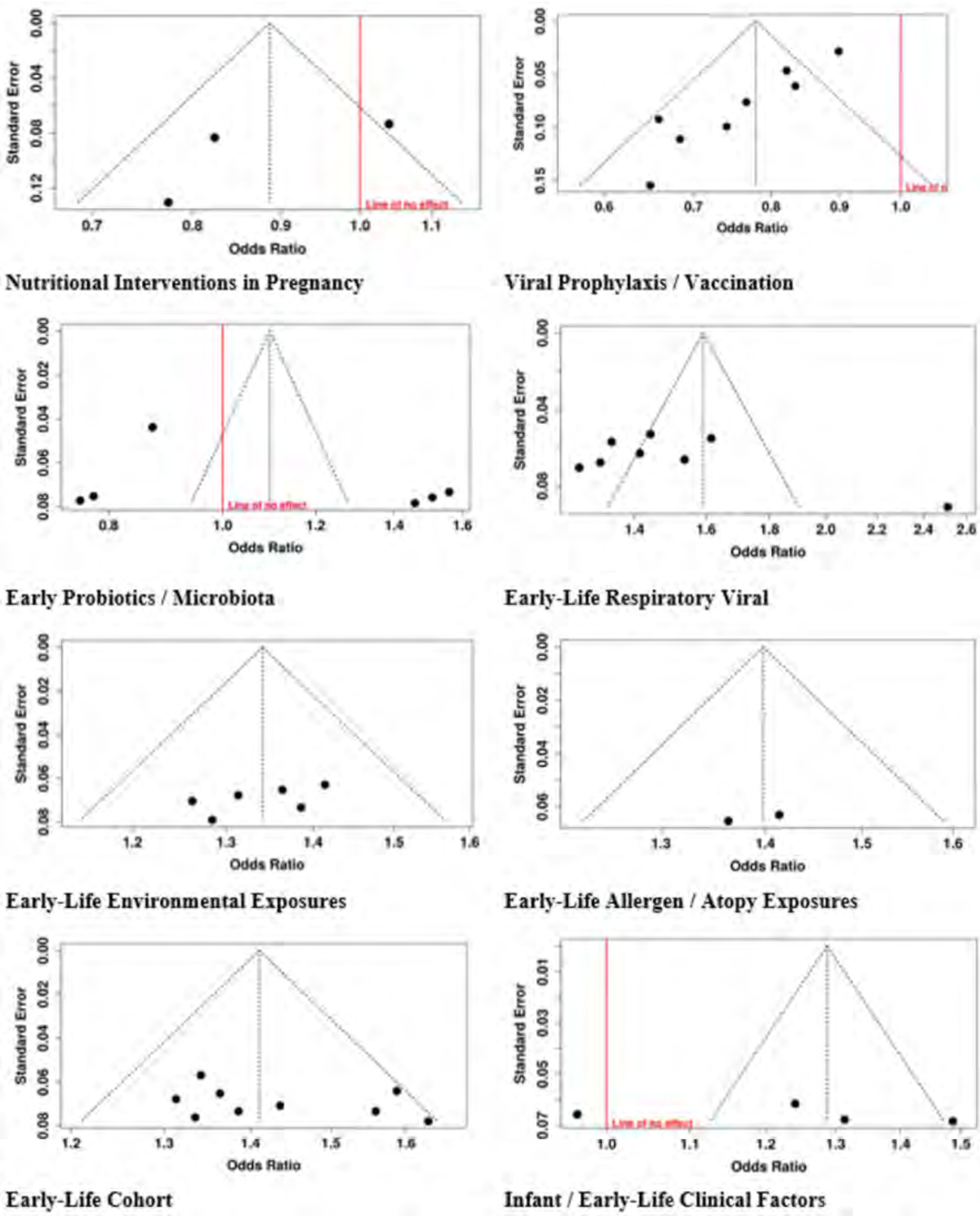

FIGURE 11
Funnel plot of studies.

The risk of developing childhood asthma and wheeze and atopy increases after children experience early-life exposure to respiratory viral infections (RSV and rhinovirus) and allergen/atopy (OR = 1.59, 95% CI: 1.39–1.82; I^2 = 90% and OR = 1.40, 95% CI: 1.30–1.50). The presence of environmental factors like air pollution and moisture damage and formaldehyde exposure led to an increase in asthma and allergic conditions (OR = 1.34, 95% CI: 1.27–1.42).

Infants who exhibited severe bronchiolitis and weighed less than normal at birth and received different types of feeding exhibited an increased likelihood of developing asthma during childhood and adulthood. The research proved that early-life risk elements continuously impacted the development of asthma and allergic disorders throughout the duration of long-term studies.

The research found publication bias for studies about viral prophylaxis and respiratory infections and allergen exposure, but all other study categories maintained their scientific strength. The research identified early-life viral exposures and allergens, environmental pollutants, and clinical factors as primary risk factors, but nutritional and probiotic interventions produced minimal and unpredictable results.

Our study which examined maternal dietary supplement studies that included fish oil and vitamin D showed no evidence that these supplements could reduce the risk of wheeze or asthma or problems with offspring development. The combined effect showed high heterogeneity because different studies used different study designs and dosing methods and tested various population groups (OR = 0.89, I^2 = 68%). The nutrients showed evidence of possible immunomodulatory effects according to previous literature, but our research indicates that typical dietary supplements do not provide enough defense against respiratory problems that develop during childhood.

The combination of viral prophylaxis treatments which include palivizumab for RSV and maternal influenza vaccination showed strong statistical evidence that it protects against recurrent wheeze and asthma and lower respiratory tract infections (OR = 0.78, I^2 = 68%). The interventions show especially strong results with high-risk infants while they also demonstrate the need for early life preventive programs which should focus on viral pathogen control. The study showed evidence of publication bias which makes it necessary to approach the study results with caution.

Probiotics and gut microbiota interventions showed no overall significant effect on asthma or atopy (OR = 1.10, I^2 = 96%). The studies demonstrate high heterogeneity because they used different probiotic strains and dosages and timing and study populations. The research shows that although gut microbiota affects immune system development probiotic supplements do not function as effective allergy and respiratory disease prevention methods.

Early-life RSV and rhinovirus infections increased risk of wheeze and asthma to 1.59 times base rate (OR = 1.59, I^2 = 90%). The immune system gets disrupted by viral infections which leads to airway remodeling that makes children vulnerable to developing chronic respiratory diseases. The research demonstrates that high-risk groups need protective measures against early viral infections.

People who experienced air pollution and formaldehyde exposure and indoor moisture damage showed increased asthma and rhinitis and eczema rates (OR = 1.34, I^2 low). The studies showed low heterogeneity which means that all studies produced similar results. The research shows that public health systems need to implement environmental solutions which include better indoor air quality and decreased pollutant exposure.

The research found that early childhood exposure to allergens which included dust mites and cat allergens and perennial sensitizers resulted in a higher asthma and wheeze and atopy risk (OR = 1.40). The uniform allergen exposure risk factor was established through research results which showed minimal variation between studies. The strategies which enable children to avoid allergens during their early years serve as effective methods to protect their health.

The study found that bronchiolitis severity, low birth weight, and feeding modes in infants were linked to increased asthma risk, which persisted into both childhood and adulthood (OR = 1.29 I^2 = 82%). These factors probably show both inherent weaknesses and early environmental experiences, which makes it essential to monitor high-risk infants for their preventive care needs.

The research showed that early life factors, which included infections and environmental factors and clinical elements determined the development of asthma and allergic diseases throughout life (OR = 1.41, minimal heterogeneity). The findings demonstrate that early-life periods serve as crucial times for implementing intervention programs.

The assessment of publication bias demonstrated that studies on viral prophylaxis and their early respiratory infections and allergen exposure research showed more positive results than actual results. The research demonstrated strong findings for nutritional interventions and probiotics, environmental exposures, clinical factors, and cohort studies. Researchers need to recognize potential bias because it affects their ability to interpret effect sizes and reach conclusions.

The findings demonstrate that early-life viral infection prevention strategies, environmental pollution reduction methods, allergen exposure control, and high-risk infant monitoring will effectively decrease asthma and allergic disease rates. Nutritional and probiotic interventions provide supportive benefits but fail to function as effective preventive methods when used independently. Public health initiatives should prioritize environmental control, vaccination, and targeted monitoring in early life.

4.2 Comparison with previous studies

In light of several limitations, the results of this meta-analysis have to be interpreted. The included randomized trials were mostly of high methodological quality, but differences in types of interventions, durations of follow-up, and ways of measuring outcomes may make it difficult to compare the studies directly. Additionally, some trials used small sample sizes, which affected the statistical power to detect differences for some of the outcomes. These limitations are in line with the observations made in the past large-scale observational and meta-analytic research. For example, van Meel et al. (74) studied more than 150,000 European children and similarly pointed out the problem of heterogeneity in the definitions of exposure and assessments of the outcome when studying early-life respiratory infections and later asthma risk. In a similar vein, Jin et al. (75) and Wang et al. (76) spot different methodological issues in the basic research, for instance, different diagnostic criteria for bronchiolitis and asthma. This puts the results into such a situation that it is not easy to give a precise interpretation and thus, strong conclusions cannot be drawn. By the way, Wadhwa et al. (77) and Liu et al. (78) brought up the issue of unmeasured confounding factors like genetic predisposition or environmental influences, which even raises the question if atopy, virus type, and household environment play a role in shaping the long-term respiratory fate. Even though the analysis revealed that publication bias was minimal, the use of only published data still requires some caution. The findings from our study, notwithstanding the limitations, have significantly supported the previous literature and even gone beyond it. We meta-analyze the randomized controlled trials, which supply a higher certainty regarding causal relationships than the mainly observational evidence that van Meel et al. (74), Wang et al. (76), and Liu et al. (78) provided. The consistency of intervention effects—measured by the same effect sizes and very low statistical heterogeneity strengthened the already strong link that earlier research established, pointing at the role of respiratory infections in early life as a risk factor for asthma and lower lung function later on. The rigorousness of the methodology adopted here, which includes structured assessments of risk of bias, Jadad scoring, and statistical synthesis, makes the reliability of conclusions relative to the systematic reviews of Jin et al. (75) and Wadhwa et al. (77) stronger. Very importantly, the agreement between our results and the large-scale epidemiologic evidence forms a basis for the hypothesis that prevention or mitigation of early-life respiratory infections—whether it be through maternal vaccination, RSV prophylaxis, probiotics, or other early interventions—could be a significant factor in controlling the prevalence of childhood asthma.

4.3 Strengths and limitations

4.3.1 Strengths

- The research examined 62 studies that investigated eight main early-life exposure categories through 10 different research methods that included nutritional interventions, viral prophylaxis, probiotics, and environmental and allergen exposures, clinical factors, and long-term cohorts. The research used meta-analysis through random-effects models to calculate odds ratios and their 95% confidence intervals, which allowed researchers to determine overall study results because study outcomes differed between studies.
- The research used I^2 to measure heterogeneity and funnel plots and Egger's test to determine publication bias, which enabled the researchers to evaluate evidence quality and reliability through critical appraisal. The research used long-term cohort studies, which demonstrated how early-life elements create persistent effects that continue to affect asthma and allergic disease progression.

4.3.2 Limitations

- The research found high variability across multiple categories, particularly between probiotics/microbiota and nutritional interventions, which had different study population and intervention and dosage and outcome definition standards.
- The publication bias in specific categories, such as viral prophylaxis, early-life respiratory infections, and allergen exposures, created a tendency to overstate both protective and harmful effects.
- The study results faced limitations because most studies used observational or retrospective designs, which restricted researchers from establishing causal relationships while introducing multiple confounding factors.
- The research findings lose their applicability to different settings because of existing differences in geographical areas, population demographics, and intervention methods.

5 Conclusion

The development of childhood respiratory and allergic diseases depends on the impact of early-life exposures and conditions. Factors such as viral infections, environmental pollutants, allergen exposure, and infant clinical characteristics consistently increase the risk of asthma, wheeze, and atopy. Nutritional supplementation during pregnancy and early probiotics demonstrate limited protective effects according to research findings. The research results demonstrate that preventive strategies need implementation during critical early-life periods, which include reducing exposure to respiratory viruses and allergens and environmental hazards while monitoring high-risk infants. The complete early-life approach establishes itself as the fundamental method to decrease childhood respiratory and allergic disorders while establishing pathways for sustained health benefits.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

RZ: Methodology, Supervision, Resources, Writing – original draft.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

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The Effects of Noise on Children's Cognitive Performance: A Systematic Review

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Abstract

Noise exposure may interfere with concentration, learning, and executive functions. In children, in particular, the non-auditory consequences of acoustically inadequate conditions are a serious concern. This systematic review examined the evidence from 26 studies investigating the effects of noise on primary school children's cognitive and academic performance. The reviewed studies show that speech noise significantly impairs children's verbal working memory. Meanwhile, non-speech environmental noise appears to notably affect academic performance, particularly in reading. Other types of non-speech noise may, instead, even improve the cognitive performance of children, although only for children with low attentional skills. However, only a few studies have compared the impacts of speech and non-speech noise or explored noise effects across various cognitive tasks. And finally, there's a shortage of both cross-sectional and longitudinal studies assessing developmental effects. Overall, this scarcity

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limits the ability to draw robust conclusions about noise effects on children's cognitive and academic abilities.

Keywords
noise, content areas, children, research setting/place type, learning, academic skills, cognitive skills

Introduction

Children experience significant fatigue due environmental noise during learning activities at home and school. Environmental noise has been extensively studied in relation to auditory or listening tasks (Hick & Tharpe, 2002). However, the impact of noise on human cognitive performance has frequently been overlooked (Jafari et al., 2019) and little attention has been paid to how noise impacts on children's non-auditory cognitive (e.g., attention, memory; Basner et al., 2014) or learning performance (e.g., reading, writing, or math; Dockrell & Shield, 2006; Fernandes et al., 2019; Ljung et al., 2009). This systematic review aims to address this knowledge gap by synthesizing and discussing emerging literature on the cognitive effects of noise in learning contexts.

The non-auditory effects of noise on children's cognitive and academic performance may vary based on noise characteristics (continuous, intermittent, impulsive, or low-frequency) and the type of cognitive tasks performed. Background noise, either informational (e.g., speech) or non-informational (e.g. unintelligible speech or non-speech noise), can originate externally (e.g., noise from adjacent classrooms or traffic) or internally classrooms, within the classroom, as a consequence of activity-related sounds like chair movements or babbling (Shield & Dockrell, 2004). In addition, susceptibility to noise may depend on the type of cognitive or academic ability performed. For instance, performance on verbal tasks such as reading and writing, involving verbal language, and non-verbal tasks, not reliant on language production and comprehension, may differ in their vulnerability to different babble noise. In this systematic review, our primary focus will be on academic tasks (such as reading, writing, and math) and a set of cognitive functions critical to children's self-regulation in academic performance: executive functions (EF; Jacob & Parkinson, 2015).

EFs is an umbrella term for a set of higher-order cognitive skills (WM, response inhibition, cognitive flexibility) that allow top-down control and regulation of thought processes and goal-directed actions (Diamond, 2013; Karr et al., 2018; Rosenberg, 2015) and predict academic outcomes across schooling (Borella et al., 2010; Duncan et al., 2007; Gathercole et al., 2004).

Apart from noise quality and the type of cognitive task, individual factors such as age, cognitive skills or hearing loss can impact children's susceptibility to noise (Söderlund et al., 2010). Thus, noise, activity and individual factors are all considered in this systematic review to account for how noise affects primary school children's cognitive and academic performance.

The research on the cognitive effects of noise has seen growth in recent years. Mealings published a series of scoping reviews, focused on the impact of chronic and acute acoustic exposure on children's attention and memory (Mealings, 2022a), as well as on the effects of classroom noise on children's literacy skills (Mealings, 2022b), behaviors (Mealings, 2022c), and wellbeing (Mealings, 2022d). All these reviews have revealed global effects of a chronic exposure to noise, on children's literacy, particularly in terms of reading accuracy and comprehension and mental wellbeing.

However, reviews that offer a comprehensive overview of the interaction between noise, tasks, and subjects variables are, to the best of our knowledge, still lacking. A systematic and critical examination of the findings in this field can not only point to directions for future studies, but also holds practical significance. It can indeed support policy decisions aimed at managing noise in schools.

Why Are Executive Functions an Important Target?

EFs are pivotal skills in learning and academic performance as they supervise performance in academic tasks and help sustain effort in those tasks under challenging or adverse conditions, such as noise. EF skills begin to develop shortly after birth, undergoes remarkable development during the preschool years (Anderson & Reidy, 2012), and progress throughout childhood and adolescence (Best & Miller, 2010), showing more pronounced growth during preschool, early school years, and adolescence (Anderson, 2002; Moriguchi, 2014; Zelazo et al., 2003). Any disruption or disorder in executive functioning inevitably results in learning impairments and reduced academic performance.

Three key executive functions crucial for academic learning are response inhibition, WM, and cognitive flexibility. Inhibition skills start developing in preschool years, continuing until approximately 5 to 8 years old (Romine & Reynolds, 2005), encompassing cognitive and behavioral aspects. Cognitive inhibition involves suppressing internal responses or ignoring irrelevant stimuli, aiding in planning and decision-making (Anderson, 2002). Behavioral inhibition involves controlling actions. Both skills significantly impact academic achievement (Duckworth et al., 2019). Inhibitory control is vital for text decoding and comprehension (Haft et al., 2019; McClelland & Cameron, 2019) and links to proficiency in mathematics and science (Gerst et al., 2017; Purpura et al., 2017).

Working memory (WM) develops linearly from ages 4 to 14. It relies on selective attention and executive control mechanisms to allocate attentional resources across memory tasks, involving active maintenance and manipulation of information (Engle, 2002; Wilhelm et al., 2013). Comprising three interlinked components—the phonological loop for auditory-verbal data, the visuospatial sketchpad for visual and spatial information, and the central executive overseeing these systems (Baddeley et al., 2019)—WM is crucial for updating, manipulating, and guiding cognitive processes such as reasoning, language comprehension, and arithmetic calculations. And thus, also academic performance in language and mathematics correlates with WM skills (David, 2012; Purpura et al., 2017).

Cognitive flexibility involves adapting cognitive strategies and behaviors to environmental changes. It develops significantly from age 7 to 9 and reaches maturation around the age 12 (Anderson, 2002). This ability to switch between patterns of thinking and manage multiple concepts is vital for children's language development (Jacques & Zelazo, 2005), arithmetic skills (Bull & Scerif, 2001), problem-solving, creativity (Lin et al., 2014; Ritter et al., 2012), multitasking (Ionescu, 2012) and reading skills (Kercood et al., 2017).

Noise and Its Effects on Children's EFs and Academic Skills

It has been theorized that noise exposure may adversely affect children's cognitive development (Chere & Kirkham, 2021). Moreover, background noise can affect EFs concurrently and directly by diverting attentional resources or causing cognitive overload (Pichora-Fuller et al., 2016; Wetzel et al., 2021) and also indirectly by inducing distress, influencing EF development (Stansfeld & Clark, 2015; Blair, 2010). Given the crucial role of EFs in learning—requiring focus, attention, inhibition of irrelevant information, and processing relevant information in working memory—any noise-related impact on EFs may subsequently affect learning and academic achievements (van Kempen et al., 2010; Sörqvist, 2010).

Unsurprisingly, children are more susceptible to noise-induced interference than adults, both in auditory or non-auditory tasks (Klatte et al., 2013). Particularly, younger children, those with cognitive, learning disabilities, or auditory issues, may encounter the greatest challenges in handling noise intrusion (Arfé, Spicciarelli et al., 2021; Prodi & Visentin, 2015)

The Systematic Review (SR)

The systematic review aimed to address the following three research questions: (1) Do different noise sources (indoor, outdoor) and types of noise (verbal, non-verbal, or mixed) equally impact children's cognitive functioning? (2) Which cognitive abilities and academic tasks are most vulnerable to background verbal and non-verbal noise? (3) How do individual factors like age or differences in memory and attention influence the effects of noise on children's cognitive and academic performance?

Methods

The systematic review followed the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement (Page et al., 2021).

Inclusion Criteria

Studies included in this systematic review meet all of the following selection criteria:

- Language: studies are written in English;
- Year of publication: studies are published between 2005 and 2022;
- Type of study: only original peer-reviewed research articles were included in the review. Reviews, systematic reviews, books, conference proceedings, and abstracts were excluded;
- Topic: only studies addressing the cognitive effects of noise were considered. Studies evaluating the effects of noise during tasks assessing children's executive functions (such as working memory and attention) or studies analyzing the effects of noise during learning tasks, such as reading, writing, and arithmetic abilities, have been taken into account;
- Study sample: all selected studies involve participants between 6 and 10 years, corresponding to the first years of primary education. Research involving preschool children, pre-adolescents, adolescents, and adults, when considered relevant, have been used to discuss the results of the SR, but were not included in the summary table.

Studies that explored the effects of noise on auditory perception and studies in which there was no assessment of cognitive or academic skills were excluded from the SR.

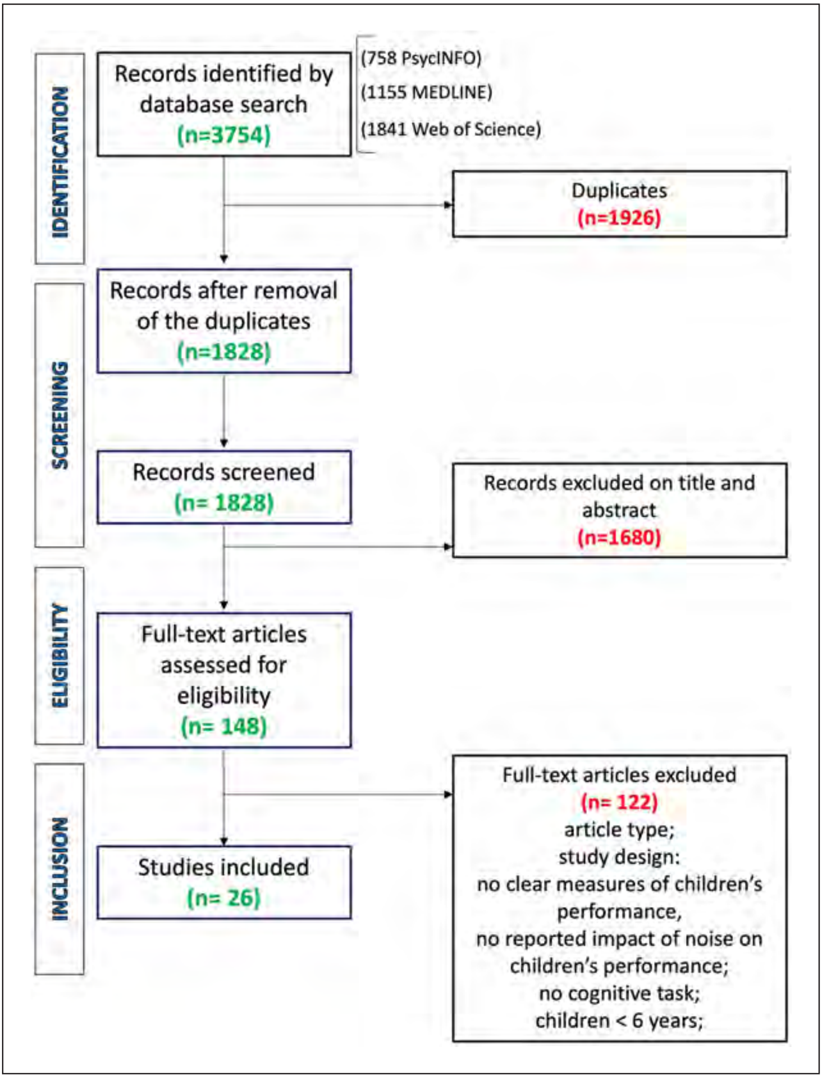

Figure 1. Database search and selection flowchart.

These inclusion (and exclusion) criteria led to the selection of 26 studies. (See Figure 1).

Search and Screening Procedures

Electronic literature search was conducted. Three databases were searched: PsycINFO, MEDLINE, and Web of Science.

Bibliographical research was performed on databanks using the following combination of keywords with the AND Boolean operator: "noise-children-classroom"; "noise-children-cognitive effort"; "noise-children-learning"; "noise-children-listening effort"; "noise-children-speech perception". Keywords "speech perception" and "listening effort," although not directly relevant to the review, were combined with "noise" and "children" as part of the search strategy to avoid overlooking potentially relevant articles where the concept of cognitive effort had also been addressed. The electronic search was conducted using Zotero software, and a search filter to limit results by publication date was applied in this initial selection phase.

In addition to this automatic electronic search, references of the articles assessed for eligibility and literature reviews, not included in the systematic review, were also examined to identify other relevant articles.

A total of 3754 records were initially identified through our literature search (PsycINFO = 758; MEDLINE = 1155; Web of Science = 1841). Following the removal of duplicates, 1,828 unique papers remained. The abstracts of these records underwent independent screening by two examiners (the first and second authors), excluding papers that did not meet one or more eligibility criteria. This process resulted in the identification of 148 candidate studies. Subsequently, the 148 full-text articles selected underwent review for potential inclusion in the systematic review. Both the first and second authors independently assessed all papers, achieving a 97% agreement. Any disagreements between the two examiners were resolved through discussion with the last author of the study to reach a consensus.

The initial disagreement between the first and second authors solely concerned the inclusion criterion related to the topic, specifically related to the type of cognitive or learning measure considered by a few studies. Disagreement between the first two authors for instance emerged when cognitive skills were measured by experimental or standardized tasks that were unfamiliar to them, thus making it difficult deciding about the study inclusion in the SR. For example, there was disagreement about including a study assessing children's creativity in quiet and noisy settings through an idea generation task (Massonnié et al., 2019). It was eventually included since the type of task allowed for the assessment of children's cognitive flexibility as an executive function. The last author, an expert in the field of cognitive assessment and learning in children with typical and atypical development, facilitated the discussion and resolution of these disagreements for those works.

Following this additional screening, 26 articles satisfied all the inclusion criteria. The most common reasons for excluding studies were: a) the paper reported measures of listening but not cognitive effort; b) measures of academic performance or executive functions (EFs) were unclear and/or insufficient information was provided to identify the dependent measure; c) measures of learning or EFs were provided, but not under noise conditions; d) the study involved preschoolers and/or older students.

Studies Coding and Quality Assessment

Starting from the identification phase, all studies were coded based on the following characteristics: author/authors; journal (peer-review or not); year of publication; publication type (experimental study, review, systematic review, book, conference proceeding, meeting abstract). Full-text articles assessed for eligibility were also categorized according to the following characteristics: sample size; task location (classrooms, other, not specified); participant age or grade level (involvement of primary school children); background noise (type and whether the study compared different types of noise); children's characteristics (cognitive or learning disabilities; hearing impairment; bilingualism).

Articles reviewed in full-text format were ultimately evaluated for their methodological rigor (e.g., being experimental or quasi-experimental studies) and relevance.

Quality Assessment

A proper study design to evaluate the impact of noise on children's cognitive performance should include a detailed description of the type of noise used during experimental tasks, along with a clear description of the tasks performed by the children. Studies were considered eligible for inclusion if they provided a comprehensive description of noise conditions, including types of noise used in experiments, sources, noise levels, and, if applicable, noise synthesis design. Additionally, studies needed to present data collected from cognitive tasks carried out under different acoustic conditions (quiet and noise, different types of noise or tasks varying in noise intensity). The cognitive tasks should be explicitly defined (e.g., in terms of measures of executive functions or learning performance) and include descriptions of the acoustic characteristics of the environments where the experimental sessions took place, task duration, and an overview of the experimental setup.

Table 1. Summary of Selected Literature Studies.

	Author (year)	Sample characteristics (age range or mean age)	Type of noise	Acoustic condition	Dependent measures	Noise effects
1	Bhang et al. (2018)	268 children (10–12 years)	Non-speech noise road traffic and aircraft noise	Acute	EFs Visual and auditory selective attention, divided attention, spatial WM, inhibition Academic skills Vocabulary, mathematics, picture arrangement	Negative
2	Brännström et al. (2019)	23 children with HL using CI and/or HA (6–13 years)	Speech noise multitalker babble noise	Acute	EFs WM	Negative
3	Clark et al. (2006)	2010 children (9–10 years)	Non-speech noise road traffic and aircraft noise	Chronic	Academic skills Reading comprehension	Mixed
4	Dockrell and Shield (2006)	158 children (mean age = 8.5 years)	Speech and non-speech noise Multitalker babble Environmental noise	Chronic	Academic skills Reading, spelling, speed of information, arithmetic	Negative
5	Dos Santos et al. (2013)	87 children (8–10 years)	Non-speech noise environmental noise	Chronic	Academic skills Reading, writing	Negative
6	Fernandes et al. (2019)	162 children (8–12 years)	Speech noise multitalker babble noise	Acute	EFs Attention Academic skills Reading, writing	Negative
7	Guerra et al. (2021)	63 children (8–10 years)	Speech noise single-talker intelligible and unintelligible speech noise	Acute	Academic skills Reading speed and comprehension	Negative
8	Helps et al. (2014)	90 sub/normal/super-attentive children (8–10 years)	Non-speech noise white noise	Acute	EFs Visuo-spatial WM, verbal WM, inhibition	Mixed
9	Howard et al. (2010)	31 children (9–12 years)	Speech noise multitalker babble noise	Acute	EFs WM	Negative
10	Jianxin and Peng (2018)	90 children (8–9 years) 90 children (11–12 years)	Speech noise speech-shaped noise	Acute	EFs Visual WM, auditory WM	Negative
11	Klatte et al. (2010)	Exp 1: 53 children (6–7 years), 47 adults (20–40 years); Exp 2: 21 children (7–9 years), 24 adults (20–35 years)	Speech and non-speech noise Single-talker speech noise Classroom noise without speech	Acute	EFs WM	Negative
12	Klatte et al. (2017)	1,243 children (7–10 years)	Non-speech noise aircraft noise	Chronic	Academic skills Reading speed and comprehension	Negative
13	Massonnié et al. (2019)	44 children (5–11 years)	Speech and non-speech noise typical classroom noise	Acute	EFs Cognitive flexibility	Mixed

(continued)

Table 1. (continued)

	Author (year)	Sample characteristics (age range or mean age)	Type of noise	Acoustic condition	Dependent measures	Noise effects
14	Matheson et al. (2010)	2,844 children (8–12 years)	Non-speech noise road traffic and aircraft noise	Chronic	EFs Episodic memory	Mixed
15	McFadden and Pittman (2008)	10 children with HL 11 children with NH (8–12 years)	Non-speech noise broadband noise	Acute	EFs Visuo-spatial WM	Mixed
16	Nagaraj et al. (2020)	125 children (7–12 years)	Speech noise multitalker babble noise	Acute	EFs Selective attention	None
17	Osman and Sullivan (2014)	20 children (8–10 years)	Speech noise multitalker babble noise	Acute	EFs WM	Negative
18	Papanikolaou et al. (2015)	676 children (9–10 years)	Speech and non-speech noise Traffic road noise Irrelevant background speech noise	Chronic	Academic skills Reading comprehension, mathematics	Negative
19	Puglisi et al. (2018)	94 second graders (mean age = 7.9 years)	Non-speech noise unoccupied classroom environmental noise	Chronic	Academic skills Reading speed and accuracy	Mixed
20	Ronsse and Wang (2013)	67 primary school classrooms (3rd and 5th grade)	Non-speech noise classroom ambient noise	Chronic	Academic skills Mathemathics, language and reading	Mixed
21	Shield and Dockrell (2008)	142 primary schools (2nd and 6th grade)	Speech and non-speech noise environmental and classroom activity noise	Chronic	Academic skills Reading, writing, spelling, mathematics, English, science	Negative
22	Söderlund et al. (2007)	21 children with ADHD 21 children without ADHD (mean age = 11.2 years)	White noise	Acute	EFs WM, attention	Positive
23	Stansfeld et al. (2005)	2,844 children (9–10 years)	Non-speech noise road traffic and aircraft noise	Chronic	EFs WM, episodic memory, sustained attention Academic skills Reading comprehension	Mixed
24	Stiles et al. (2012)	16 children with mild to severe HL 24 children with NH (6–9 years)	Non-speech noise experimental air conditioning noise	Acute	EFs WM	None
25	Sullivan et al. (2015)	20 children (8–10 years)	Speech and non-speech noise multiclassroom noise	Acute	EFs WM, auditory comprehension	Negative
26	Wang and Brill (2021)	216 primary (3rd and 5th grade) and secondary (8th and 11th grade) school classrooms	Speech and non-speech noise environmental and classroom activity noise	Chronic	Academic skills Reading, mathematics	Mixed

Note. HL = hearing loss; NH = normal hearing; CI = cochlear implant; HA = hearing aids; WM = working memory; ADHD = attention deficit hyperactivity disorder.

Results

Twenty-six articles were identified that met the inclusion criteria.

Table 1 summarizes the key information of each included study. It reports details about the study sample, acoustic conditions, type of noise utilized, dependent measures, and the nature of the noise effects.

Additionally, a comprehensive summary of all 26 articles incorporated in the review is presented in an extended supplementary table (Extended Table). This detailed summary includes the research design, experimental tasks, as well as the primary findings and observed effects.

Included Studies

Thirteen of the twenty-six selected studies assess the impact of noise on children's EF (2, 8, 9, 10, 11, 13, 14, 15, 16, 17, 22, 24, 25). Ten papers focused on children's academic and learning skills (3, 4, 5, 7, 12, 18, 19, 20, 21, 26), and three works analyzed both EFs and learning (1, 6, 23) (see Table 1).

Almost all articles ($n = 19$) reported studies that involved normally hearing children with no neurological or learning problems. Only three studies involved children with hearing loss (2, 15, 24) and other four studies analyzed, respectively, children at risk for learning disorders (1), iper and sub-attentive children (8, 22), and children with certified special educational needs (4). Only one study (11) compared children to adults' performance in noise.

Eight of the studies included in the SR explored the effects of speech noise on children's cognitive or academic performance (2, 6, 7, 9, 10, 16, 17, 25), whereas 15 studies focused on non-speech noise, such as traffic and aircraft or white noise (1, 3, 5, 8, 12, 14, 15, 18, 19, 20, 21, 22, 23, 24, 26) (see Table 1). Only two articles compared the effects of different types of noise on children's learning or EFs (4, 11) and one study used mixed noise (13).

The studies consistently highlight the detrimental impact of speech noise, such as babble noise, on memory, attention tasks, and overall learning activities. In contrast, findings regarding non-speech noise are less consistent. Both aircraft and traffic noise are reported to negatively affect children's learning and executive functions (EFs), with noise intensity playing a crucial role: children's performance generally declines with increased noise levels. Conversely, white noise, characterized by equal energy at all frequencies and often used as a masking sound, shows different effects depending on individual factors, such as presence or absence of cognitive or attentional disorders. Further details on these findings will be considered later in the discussion.

A distinction about noise type regards the acute and chronic nature of noise: acute noise refers to short-term exposure to noise, or experimentally induced loud or disruptive sounds, whereas for chronic noise researchers refer to a prolonged or continuous exposure to environmental noise over an extended period. Among the examined studies, 12 investigate the effects of chronic noise exposure, while 14 analyze the consequences of acute noise exposure. Unfortunately, only in two cases (14, 23) exposure to chronic noise was studied in relation to children's EFs. The studies have indeed primarily focused on the effects of chronic noise on learning tasks.

The Effects of Noise on Children's EF

Most of the studies focused on EFs examined the effects of acute noise on WM (2, 8, 9, 10, 11, 15, 16, 17, 24, 25) (see Table 1). Several studies investigated children's attention and inhibition skills (1, 6, 8, 16, 22, 23), and one (13) assessed noise effects on children's performance in creative tasks (e.g., idea generation tasks), which involve cognitive fluency.

The majority of studies have investigated the effects of babble noise, revealing significant negative impacts on children's verbal WM (11). Nevertheless, as real-life settings encompass complex acoustic environments comprising both speech and non-speech noise, also the effects of background non-speech noise were considered, finding that also non-speech noise can adversely affect children's EFs (1).

The studies show that children's auditory working memory (AWM) performance is consistently hindered by unintelligible multi-talker babble noise, particularly at low signal-to-noise ratios (SNRs) (9, 17, 25). SNR denotes the ratio between desired signal power and undesired signal (or background noise) power, typically measured in decibels. Lower SNRs correspond to poorer performance in children.

Osman and Sullivan (2014) found that children's WM performance decrease with increasingly degraded listening conditions, independently of the complexity of the WM tasks. Their study involved three subtests from the Working Memory Test Battery (Forward and Backward Digit Recall and a Listening Recall test) aurally administered in varying acoustic conditions (quiet, competing four-talker babble noise at 0 and −5 dB SNRs). Performance was highest in quiet conditions and significantly decreased with added noise, especially at −5 dB SNR. Interestingly, the impact of noise was similar across tasks of different complexities. Another study by Sullivan et al. (2015) revealed that children performed notably worse in multiclassroom noise compared to quiet conditions, particularly on AWM and comprehension tasks. Additionally, the relationship between AWM and listening comprehension was stronger in noisy settings, implying an increased reliance on WM during comprehension tasks in unfavorable acoustic environments.

Howard et al. (2010) employed a dual task paradigm, using a word recognition task as the primary task and a digit recall task as the secondary task, which involved displaying sets of five-digit numbers on a laptop monitor. They tested children in quiet and under varying SNRs (+4, 0, −4 dB) and found a negative effect of multitalker noise on digit recall as SNR became less favorable. In the single task condition, serial recall performance was minimally affected, but in the dual task setting, particularly at lower SNRs, there was a notable decrease of the digit recall task. According to the author, this suggests that increased effort in listening for the primary task in noise might have limited the cognitive resources available for the secondary task.

Another study (10) observed a relationship between SNR and reverberation time (RT) and performance in WM. The authors used three different RT (0.51, 0.80 and 1.18 seconds) and three different SNR conditions (3 dB(A), 9 dB(A), and 15 dB(A)) to investigate the effect of speech-shaped noise and reverberation on WM in 19 third and 19 sixth grade children. The findings indicated that as SNR increased and RT decreased, WM span scores also increased. Moreover, older children tended to achieve higher WM scores than younger children in similar acoustical settings.

Remarkably, in children with hearing impairment, WM performance appears to be affected by babble noise even in more favorable SNR conditions. Brännström et al. (2019) found that at 10 dB SNR, multi-talker babble noise notably decreased the serial recall performance of children with cochlear implants or hearing aids during a verbal WM task. These outcomes suggest heightened susceptibility to noise effects among children with hearing loss compared to typical hearing peers.

Regarding non-speech noise, like environmental and broadband noise, the findings are less consistent. Stiles et al. (2012) simulated air conditioning noise by filtering a broad-spectrum signal to match the noise used in a prior study. At low levels of simulated air conditioning background noise, they observed no impairment in working memory performance among children with mild to severe hearing loss or those with normal hearing. In another study (15), the impact of noise and hearing status on multitasking was examined. Children, both with minimal hearing loss and those with typical hearing, were asked to perform a word categorization task while performing some dot-to-dot games, in quiet and in broadband noise. The completion of dot-to-dot games was slower under multitasking conditions. Surprisingly, the dot rate was affected similarly in both quiet and noisy settings for both hearing-impaired and typically hearing children, despite the hearing-impaired children experiencing challenges with the word categorization task.

One of the most informative studies on classroom acoustics' impact on children's performance is Klatte et al.'s (2010). They investigated how irrelevant speech (a professionally read newspaper article) and typical classroom noise (typical mix of non-speech classroom noise, such as moving chairs, scraping feet and coughing) affected memory recall of visually presented common nouns. Both experiments had sound levels between 53 and 56 dB(A). The first tested first graders and adults with fixed list lengths; the second adjusted sequence lengths for individual spans, involving adults and second-to-third graders. Irrelevant speech equally affected both children and adults, while non-speech noise didn't impact performance significantly. First graders performed better in silence compared to classroom noise. The finding that the impact of irrelevant speech is unrelated to age contrasts with Elliott's (2002) study, where younger children were more affected. However, as noted by Klatte et al. (2010), the irrelevant speech was around 55 dB(A), while in Elliott's study, it reached 72 dB(A). Additionally, Klatte et al. (2010) used an unknown foreign language as irrelevant speech, whereas Elliott used the participants' native language. Overall, these findings suggest that louder sounds and meaningful speech, such as those used in Eliot's study, can significantly impair younger children.

The largest study on children's response to aircraft and road traffic noise is the RANCH project (Road traffic and aircraft noise exposure and children's cognition and Health; 23). This cross-national, cross-sectional study evaluated chronic noise exposure's impact on 2,844 children aged 9 to 10 from 89 primary schools near airports in the Netherlands, Spain, and the UK. Cognitive tests administered in class revealed no impact on children's sustained attention from aircraft or road traffic noise. However, a linear relationship was observed between aircraft noise exposure and impaired memory recognition.

A subsequent study (14), part of the RANCH Project, focused on the effect of chronic aircraft and road traffic noise on children's episodic memory, assessing delayed cue recall, delayed recognition, and prospective memory. Surprisingly, the findings were mixed: aircraft noise was found to be related to impaired memory recognition, while exposure to road traffic noise showed an unexpected association with improved cue recall. Instead, no significant associations were found between aircraft noise exposure and cued recall or prospective memory, nor between road traffic noise and recognition or prospective memory.

Although the effects of speech noise have been primarily explored in relation to memory tasks, some studies suggest that babble noise can also significantly affect children's sustained attention. Fernandes et al. (2019) tested children aged 8 to 12 years, revealing that a 20 dB increase in speech noise, above the level of environmental noise, did not affect sustained attention performance. However, exposure to 40 dB of babble noise significantly reduced children's attention, with noise effects being age-independent.

Nagaraj et al. (2020) assessed children aged 7 to 12 using a dichotic listening task to measure selective attention with and without multitalker babble. Noise susceptibility was quantified by error differences between these conditions, showing no significant correlation with age. Furthermore, there was no correlation observed between the extent of susceptibility to auditory distraction and the WM capacity of children.

In a study by Bhang et al. (2018), road traffic and aircraft noise had negative effects on children's attention and cognitive performance. This study included a large number of children (268 elementary school students aged 10–12) who completed various EF tests measuring selective visual and auditory attention, divided attention, spatial working memory, cognitive inhibition, and attention allocation. A first group of children was exposed to background noise at 43.5 to 46.1 dB, while a second group was exposed to additional background noise of 15 to 17 dB (60.8–62.8 dB). The noise was a combination of road traffic and aircraft noise. Across tests, children exposed to higher noise levels generally scored lower. Significant differences emerged between groups, notably in response time for auditory attention, memory span, and correct responses in spatial working memory tasks. These noise-related differences also appeared between children with differing academic performance levels, suggesting a stronger impact of traffic noise on those with learning difficulties. We decided to include this study, despite the participants' age being slightly older, as children's grade level falls within the range considered in the SR.

Based on preliminary findings suggesting improved creative processes for adults in a moderate-noise environment (Mehta et al., 2012), Massonnié et al. (2019) explored the impact of noise (speech fragments, movement, and external noise) on children's creativity in two idea generation tasks. Creativity and learning are interrelated, with the process of generating new ideas strictly associated with learning and changes in knowledge or behavior (Pang, 2015). The authors investigated the role of working memory, attention, and age in regulating the noise effect on creativity, discovering a negative impact of noise on creative processes, especially in younger children (5–8 years) with lower selective attention skills. These children provided fewer original ideas in noisy conditions, while those with higher selective attention were generally unaffected by noise.

As noted earlier, despite the consensus on the negative impact of background noise, not all studies consistently demonstrate impaired cognitive performance in children exposed to noise. For instance, Söderlund et al.

(2007) reported a positive effect of noise on children with Attention-deficit-hyperactivity disorder (ADHD). In their study involving 42 children aged 9 to 13 years, with 21 diagnosed with ADHD, working memory and attention were assessed using a Self-performed task (SPT) for high recall and a Verbal task (VT) for low recall. The children were tested in both quiet and white noise conditions (white noise at 81 dB A). Results indicated that white noise improved the performance of the ADHD group but hindered the performance of the control group.

Another study by Helps et al. (2014) confirmed the positive impact of white noise on children's attention skills. They explored how varying white noise levels affected children with different attention abilities. Their results validated that background white noise enhanced performance in inattentive children while hindering attentive ones. Assessing 25 super-attentive, 29 typically developing, and 36 sub-attentive children aged 8 to 10 using non-EF tasks (verbal episodic recall and delayed verbal recognition) and EF tasks (visuospatial working memory and Go-No-Go), they found that moderate white noise (75 dB) significantly decreased performance only in the super-attentive group for non-EF tasks. For EF tasks, the sub-attentive group showed significantly improved performance with a shift from low (65 dB) to moderate (70 dB) white noise, while the other groups didn't exhibit significant effects.

Studies on the Effects of Noise on Children's Academic Skills

The studies evaluating the effects of noise on children's academic skills have mainly focused on reading ($N = 7$), and in particular, both on reading speed and reading comprehension. Reading speed, crucial in determining reading fluency or automaticity, is a key measure in assessing reading proficiency. Proficient readers typically exhibit fluent reading, but may experience slower speeds when encountering inconsistencies in text.

Guerra et al. (2021) assessed the reading skills of 63 third- and fourth-grade children in a single-talker speech-noise condition. The noise, either intelligible or unintelligible, was presented at two intensity levels (45–50 dB and 65–72 dB SPL). The study revealed that reading measures (fluency and comprehension) were differentially affected by acoustic (noise intensity) and semantic (speech noise intelligibility) characteristics. Reading speed was notably slowed by increasing speech-noise intensity, while higher intelligibility did not significantly impact it. In contrast, reading comprehension was more influenced by the semantic aspect, particularly affected by intelligible speech. Unlike reading speed, comprehension showed no significant sensitivity to noise intensity. Additionally, the intelligibility effect on comprehension was more pronounced in children with lower interference control, as indicated by lower scores on an auditory Stroop task.

Also, Bhang et al. (2018) study, described in the section dedicated to the effects of noise on EFs, tested the effects of noise intensity on reading speed, finding that reading speed was significantly affected by traffic noise (60.8–62.8 dB), that is, when children were exposed to an additional 15 to 17 dB over background noise. Contrasting results are reported by Fernandes et al. (2019). The authors investigated the influence of multitalker noise on reading speed among third, fourth, and fifth graders. While reading time progressively increased for fifth graders with noise exposure, it surprisingly decreased for third and fourth graders.

Another study by Puglisi et al. (2018) investigated the impact of classroom acoustics on the reading speed of 94 second-graders across three primary schools. The authors analyzed the effects of speech clarity (C50), a measure of sound power within the first 50 milliseconds of the impulse response and thereafter (Rakerd et al., 2018), as well as reverberation. The results showed a significant association between reading speed and speech clarity, while non-significant correlations with reverberation were found.

The absence of reverberation effects aligns with Ronsse and Wang's (2013) findings. They investigated unoccupied classroom acoustical conditions, including background noise level and reverberation time, on third- and fifth-graders' achievement scores. Ronsse and Wang observed non-significant correlations between reverberation time (RT) and children's achievement. Additionally, significant negative correlations were found between background non-speech noise levels and language and reading scores of fifth-graders, while none of the background noise conditions significantly correlated with third-graders' achievement scores.

In a large-scale study, Papanikolaou et al. (2015) assessed the effects of noise on children's reading comprehension, finding different results from Guerra et al. (2021). Indeed, Papanikolaou et al. found a negative relationship between non-speech noise intensity and reading comprehension performance. The study involved 676 children aged 9 to 10 years from schools located in an area with a homogenous socioeconomic background. Participants were classified into three groups based on the level of exposure to traffic noise and found that children in low-level noise schools (55–66 dB) scored significantly better in reading comprehension than those in medium (67–77 dB) and high (72–80 dB) level noise schools.

Also in the RANCH study, researchers examined the link between aircraft and road traffic noise exposure intensity and reading comprehension (23; 3).

They analyzed this relationship in over two thousand 9 to 10-year-old primary school children, using nationally standardized tests for reading comprehension. The findings, consistent across Netherlands, Spain, and UK, revealed a significant association between prolonged exposure to aircraft noise at school and lower reading comprehension. This effect wasn't influenced by sustained attention, working memory, or episodic memory. The dimension of the effects remained consistent across studies, with a 5 dB difference in aircraft noise linked to a 2-month reading delay in the UK and a 1-month delay in the Netherlands. However, chronic exposure to road traffic noise at school didn't show significant effects on reading comprehension. The authors suggested that the more intense and unpredictable nature of aircraft noise, along with its transient disruptions, might impair children's concentration more than traffic noise, which is generally more predictable.

Klatte et al. (2017) obtained similar findings in a study on aircraft noise effects on reading, related verbal abilities, quality of life, and annoyance. Despite aircraft noise levels did not exceed 59 dB in the analyzed schools (compared to 77 dB in the Ranch Project), significant associations were observed between aircraft noise exposure and reduced reading performance. These effects were evident in a standardized reading assessment's global score, comprising three subtests assessing reading speed and accuracy for words, sentences, and short paragraphs. Interestingly, the impact of noise wasn't significant in analyses of children with a migration background, a condition often linked to lower reading achievement in European countries.

Other studies have linked noise to reading and writing accuracy. Dos Santos et al. (2013) assessed reading and writing performance in relation to level of noise in school environment and the use of lexical and phonological reading routes. Children exposed to school noise levels detrimental to the auditory integrity, above 80 dB(A), exhibited poorer performance compared to those exposed to levels below 80 dB(A), with impaired use of both phonological and lexical routes in reading and writing. Accuracy scores for nonwords were higher in children exposed to lower noise levels, indicating a general decrease in the use of both routes in those exposed to noise above 80 dB(A). Similar findings were reported by Fernandes et al. (2019), who tested children aged 8 to 12 in three conditions: exposed only to natural environmental school noise, with an additional 20 dB of interference noise (children's loud conversation), and with interference noise produced at a level of 40 dB. In the case of 40 dB added to environmental noise, the authors observed more errors, particularly in nonwords, during a spelling dictation task, indicating a negative impact of noise on children's sublexical spelling procedures.

A few studies also report negative effects of noise on children's mathematical performance. For instance, children attending schools with environmental low noise levels (55–66 dB) tend to score better on mathematical tasks compared to those in high noise level schools (72–80 dB) (18). Additionally, arithmetic scores decrease when children are exposed to an extra 15–17 dB over a moderate traffic and aircraft background noise level of 43.5 to 46.1 dB (i.e., a level equal to 60.8–62.8 dB) (1).

Wang and Brill (2021) assessed 216 classrooms across four grade levels (3rd, 5th, 8th, and 11th grade children) for math and reading skills. They measured the average daily A-weighted equivalent level of non-speech noise, the daily difference between A-weighted equivalent levels of speech and non-speech noise (as a signal-to-noise ratio measure), and the mid-frequency averaged reverberation time. A significant correlation was observed between higher daily non-speech noise levels and lower math performance, while no significant noise effects were found on children's reading performance (26). Contrary, other studies (e.g., 20) found that classroom background noise levels are not significantly correlated with math test scores.

A comprehensive study on noise's impact on academic performance in the classroom is by Dockrell et al. (2006). They assessed the effects of speech and non-speech noise (multitalker babble noise and environmental noise, e.g., sirens and lorries) on reading, spelling, arithmetic, and nonverbal (speed of information analysis) tasks. The study involved 158 primary school children tested under three noise conditions: quiet, classroom babble noise, and babble noise mixed with traffic environmental noise. Performance on all tasks was lower in the babble noise condition compared to quiet, while nonverbal task performance was significantly better in quiet than in both babble and babble plus environmental noise. An unexpected finding was that in reading and spelling, children performed better in the babble plus environmental noise condition than in quiet. The authors speculated that this third noise condition might have encouraged children to actively focus on the task, redirecting their attention.

In a subsequent study by the same authors (21), the effects of chronic exposure to environmental (external) and classroom (internal) noise on primary school children's academic achievements were examined. Standardized Assessment Tests (SATs) measured children's attainments in reading, writing, spelling, mathematics (year 2), and English, mathematics, and science (year 6). Academic scores were correlated with noise levels and acoustic parameters inside and outside primary schools in different London boroughs. The study included outer and inner boroughs, excluding those exposed to aircraft noise. The findings revealed a detrimental effect of chronic exposure to both external and internal noise on children's academic performance.

External noise, particularly road traffic, had a significant negative impact on academic performance, with a greater effect on older children. In outer boroughs, mathematics was most affected by external noise, while in inner boroughs, it was English. Reading scores were negatively associated with external noise levels in all boroughs. The internal noise parameter most closely related to test scores was L90 (the A-weighted sound pressure level exceeded for 90% of the time interval considered) in occupied classrooms, showing significant correlations with all subjects except spelling (in second graders) and mathematics (in sixth graders).

Discussion

The SR had three main goals: (a) Analyze the different sources and types of noise in terms of their cognitive effects and impact on children's learning; (b) Evaluate which executive functions and academic tasks are more susceptible to the influence of both verbal and non-verbal noise; (c) Try to understand how individual factors such as age or variations in memory and attention affect or mediate the impact of noise on children's cognitive and academic performance.

Noise Sources and Noise Types

The analysis of relevant studies confirms that, both speech (babble) and non-speech (e.g., traffic, aircraft) noise, generally have a negative impact on children's cognitive and academic performance.

Speech noise seems to have a particularly negative effect, although its impact has been examined mainly in relation to verbal WM or attentional skills. Non-speech noise, such as traffic or aircraft noise, has been found to negatively affect children's academic abilities, such as reading, math and writing.

However, it is noted that not all noise effects are consistently negative; certain non-speech noises, such as white noise, can positively influence cognitive performance by improving attention, especially in children with attentional problems.

When analyzing the impact of different types of noise, it's crucial to distinguish whether the study under examination follows an experimental or correlational approach. It is indeed crucial to note that, while experimental studies establish causal relationships between noise exposure and cognitive performance, correlational studies cannot demonstrate cause-and-effect connections. It can indeed be said that experimental studies have an advantage over correlational ones because they allow direct manipulation of noise conditions. This enables a clear comparison between noisy and quiet environments, resulting in a more accurate understanding of the direct effects of noise exposure.

In this literature review, which encompasses both experimental and correlational research, it can be noted that the impact of noise on EFs has been primarily analyzed by experimental studies, thus mainly focusing on the effects of acute noise.

Conversely, the analysis of the association between noise and academic performance has mostly been carried out through correlational studies, primarily assessing learning outcomes in association with chronic environmental noise exposure. This consideration, coupled with the unfortunate scarcity of studies directly comparing the effects of different types or sources of noise, results in insufficient evidence to conclude equivalent harm among different types of noise on children's cognitive performance.

Experimental studies highlight that acute verbal noises negatively impact verbal WM, while correlational studies show chronic non-verbal noise adversely affects children’s academic performance, especially in reading. In both cases, noise intensity plays a crucial role. However, comparing the effects of different noise types on the same task or the same noise type on different cognitive tasks remains challenging.

Finally, it has emerged that almost all experimental studies have used homogeneous and continuous noise. Regarding the different nature of noise and its various sources, it is worth considering that transient noise might disrupt performance more than continuous noise. Therefore, the transient or continuous nature of the noise, in addition to its source (traffic or indoor speech noise), could be the crucial factor in explaining the effects of noise on children's cognitive performance. In future studies, it would be interesting to experimentally compare the effects of both continuous and transient noise.

Cognitive Effect of Verbal and Non-Verbal Noise

Effects on Children’s EF. Researches investigating noise's impact on children’s EFs mainly tested acute noise effects on tasks conducted under controlled noise conditions. The sole study exploring the correlation between chronic noise exposure and episodic memory found a linear relationship between exposure to aircraft noise and impaired recognition memory in children (14).

The studies on noise’s impact on EFs have focused on a limited range of EF skills, primarily verbal ($N=8$) and non-verbal ($N=6$) working memory (WM), and attentional skills ($N=4$). The entirety of studies examining the effects of acute verbal noise on verbal WM has found negative effects of verbal noise, often through the Irrelevant Speech Effect (ISE). In the ISE, multitalker babble or similar irrelevant speech impairs serial recall in verbal tasks like recalling digits, letters, or words (Elliott & Briganti, 2012). Two explanations exist for this effect: the first suggests that working memory (WM) impairment occurs because irrelevant speech redirects attention away from the memory task. As this phenomenon relies on attentional resources, any noise, not just irrelevant speech, diverting attention may act as a distractor. The second explanation suggests that the effect arises from the automatic intrusion of irrelevant speech fragments into the verbal rehearsal process of the phonological loop. Here, only speech noise is believed to disrupt the verbal WM process due to its automatic encoding in verbal WM (11). Our systematic review challenges the attentional origin of the Irrelevant Speech Effect (ISE). Some studies indeed found no significant effects of non-speech noise on verbal working memory (WM) (11; 24). Only visuo-spatial WM performance was impacted by non-speech noise (1; 8; 10). Generally, the finding that speech is more distracting in verbal WM tasks than non-speech noise supports the phonological interference hypothesis of the ISE. This holds at least for older children and adults, who have developed rehearsal skills (Elliott & Briganti 2012) and greater control over their attentional processes. In younger children, more susceptible to distraction, attentional resources may have a greater role in the ISE. For example, Klatte et al. (2010) discovered that WM impairments due to non-speech noise were age-related, affecting only first-graders but not older children or adults.

Few studies have investigated the impact of noise exposure on attention, often considering attention as a mediating variable. Research on acute noise effects on attention indicates negative impacts on various attention types—visual sustained (6), selective, divided (1)—from both speech (6) and non-speech noise (1), with louder noise intensifying these effects. In summary, while children may adapt to noisy settings, heightened noise levels make sustaining attention and focus challenging. In contrast, chronic noise appears to have no significant effect on children’s attentional skills. For example, Stansfeld et al. (2005) observed that neither aircraft nor road traffic noise affected sustained attention.

Effects on Academic Skills. Unlike studies focusing on EFs, research investigating noise’s impact on learning performance have been primarily focused on chronic noise effects. Within learning skills, reading abilities have received most attention. All studies reveal that reading is significantly affected by both indoor and outdoor environmental classroom noise, which impacts various aspects of reading (speed, accuracy, comprehension). The majority of these studies (3; 4; 12; 18; 20; 21; 23; 26) analyzed the impact of non-speech noise like aircraft, traffic, and environmental noise. Fewer studies (4; 6; 7) evaluated reading under speech noise conditions.

Guerra et al.'s (2021) experimental study on acute noise and reading is particularly relevant here, revealing that speech noise's aspects like loudness and intelligibility affect reading differently. Whereas speech noise loudness seems crucial for reading speed, intelligibility seems a key factor in reading comprehension. These effects stem from distinct roles played by perceptual and semantic processes in word recognition (reading speed) and comprehension. Louder noise slows early reading processes like letter-sound connections, while intelligible speech noise disrupts verbal working memory, engaging automatic semantic processes that hinder comprehension-relevant processes (Marsh et al., 2009). Guerra et al. (2021) study emphasizes the need for a thorough exploration of the specific cognitive mechanisms underlying noise interference in learning tasks.

Other studies on chronic noise effect have found that children's reading comprehension is also impaired by non-speech noise (3; 23). These findings suggest that other types of interference, involving attentional resources, should be considered when assessing performance in complex academic tasks such as reading comprehension.

Arithmetic performance has also been examined in multiple studies, revealing impairment by both speech (4) and non-speech noise (1; 4; 18; 21; 26). Only one study, by Ronsse and Wang (2013), found no significant correlation between higher background noise from building mechanical systems and math achievement scores, whereas it was significantly correlated with reading comprehension. However, the noise levels in this study (ranging from 36 to 50 dBA) were generally lower compared to the other studies, suggesting that higher noise levels may be required to impair mathematical skills compared to reading skills.

The fact that only a few studies have examined the effects of noise on writing, discovering negative impacts, represents a significant gap in current literature. Writing tasks demand substantial linguistic, cognitive, and executive function resources (Arfé, Festa, et al., 2021; Berninger & Winn, 2006; Dockrell et al., 2019). Task-irrelevant sounds could impair writing by contrasting the cognitive processes involved and diverting attention. Writing proficiency involves various phonological, semantic, and syntactic processes, making it susceptible to disruption by irrelevant background speech. Background speech creates conflicts between phonological and semantic processes, notably affecting word generation within phrases and worsening semantic and grammatical accuracy in writing (Sörqvist et al., 2012).

Individual Differences and Susceptibility to Noise

The SR showed that age is a predominant factor influencing children's susceptibility to noise. Generally, studies indicate that younger children exhibit lower performance under noise conditions compared to older peers and adults. As children grow, their developing EF enable them to handle classroom distractions, coinciding with improvements in academic skills like reading and writing, potentially reducing also vulnerability to noise disruptions at certain levels.

However, the findings from the reviewed studies display inconsistencies. Some research indicates a contrasting pattern, suggesting a heightened impact of noise on older children compared to younger ones. Notably, across studies where younger children exhibited greater susceptibility to noise (10, 11, 13), the focus was on assessing noise effects on EFs. Conversely, studies highlighting a stronger impact of noise on older children (6, 20, 21) centered on learning tasks like reading and writing. One plausible explanation for these disparities could stem from the developmental stage: younger children might be more susceptible to noise disruptions concerning EFs due to ongoing cognitive development, affecting their ability to concentrate and filter distractions. In contrast, older children engage in academic tasks that necessitate more complex cognitive abilities, thus making them more susceptible to noise interference as these tasks demand deeper and more elaborated information processing. In any case, these findings emphasize the need for comprehensive exploration of the relationship between children's age and cognitive performance in noisy settings.

Above age, also individual differences in cognitive skills can influence/mediate the impact of noise on children's performance. Sullivan et al. (2015) discovered a strong connection between higher verbal WM scores and improved performance on comprehension tasks in noisy environments. This suggests that a child's ability to compensate for noise depends on their WM capacity. However, like for age effects also for the role of individual differences in cognitive skills findings are not always consistent. Nagaraj et al. (2020) found no significant correlation between susceptibility to speech noise and individual differences in WM capacity: children with greater WM capacity were not better at ignoring interference from speech noise than those with low WM capacity. These results indicate that the attention-controlled WM system may not effectively suppress the noise effect.

Nevertheless, if cognitive resources play a crucial role in mediating the cognitive effects of noise, children with developmental or learning disabilities might experience more significant challenges in noisy environments. Few studies have focused on special needs populations, including children with hearing loss or attentional deficits (2; 4; 8; 15; 24), sometimes revealing unexpected findings.

For instance, Söderlund et al. (2007) and Helps et al. (2014) found an inverse relationship between attention skills and white noise effects, supporting the stochastic resonance hypothesis. This theory suggests that noise in a non-linear system can enhance output signal quality (McDonnell & Ward, 2011). This phenomenon applies to various physiological systems; for example, noisy (stochastic) stimulation can be linked to improved cognitive functions. White noise, known for its equal intensity across frequencies, has shown positive effects on learning and memory, notably in ADHD and reading disability cases (Arfé et al., 2022; Pickens et al., 2019; Rausch et al., 2014; Söderlund et al., 2010, 2021). These benefits might involve dopaminergic neuromodulation and improved connectivity between midbrain regions and the superior temporal sulcus, critical in attention modulation. The Moderate Brain Arousal model (MBA) indicates that dopamine levels regulate the optimal noise level for cognitive performance, suggesting ADHD individuals might require more noise. In light of this, the findings from Helps et al. (2014) and Söderlund et al. (2007) are particularly relevant as they suggest that noise effects can vary based on the characteristics of the exposed subjects and underscore the importance of considering the interplay between noise and individual characteristics.

Limitations in the Current Literature and Future Directions. While research on noise's impact on cognitive performance and learning has grown in the last two decades, this review highlights significant literature gaps. Few experimental studies (1; 6; 7) examine acute noise effects on learning or compare how different noise types affect the same cognitive tasks or populations. To our knowledge, except for Dockrell and Shield (2006), no studies compare speech and non-speech noise effects on primary school children's academic performance, providing a significant area for further investigation.

Furthermore, we found only one study (7) comparing, verbal noise masking types: single talker, four talkers, multitalker noise. Such a comparison could be crucial in understanding speech noise interference. For instance, assessing the impact of the number of talkers on informational masking, which involves semantic interference at higher auditory and cognitive processing levels, may help elucidate how speech noise affects children's cognitive performance (Jagadeesh & Uppunda, 2021). Fewer talkers in masking noise make distracting information more intelligible to listeners (Dekerle et al., 2014). Conversely, babble noise generated by many talkers can remove much of its informational content, rendering speech unintelligible (Van Engen et al., 2014) as multitalkers can mask each other. However, speech noise may still be a relevant (social) signal for children even when non-intelligible (Arfé et al., 2022). Contrasting these speech-noise conditions could aid in understanding how speech-noise impacts children’s cognitive performance at school.

In the field there is also scarcity of comprehensive analyses focused on the interaction between noise characteristics and cognitive tasks. Although some studies in this SR addressed this issue (1; 4; 6; 23), the literature remains limited with few replications and inconsistent findings. For instance, Dockrell and Shield (2006) discovered that conditions assumed to be worse for noise, like combined noise sources, didn’t necessarily produce stronger reading interference compared to isolated noise sources. Moreover, the same noise interference may have different effects across learning tasks, such as reading, writing, or math.

Another note concerns the scarcity of longitudinal studies on the causal impact of chronic noise exposure. Despite acute noise demonstrating immediate effects, evidence suggests that prolonged noise exposure significantly affects children's cognitive development over time. Conducting longitudinal studies, particularly in examining complex environmental factors like chronic noise, is inherently challenging. Chronic environmental noise exposure often coincides with residing in low socio-economic status areas, near airports or train stations (Dale et al., 2015), and is linked to various health conditions such as distress, annoyance, sleep disturbances, metabolic issues, and heart disease (Clark & Paunovic, 2018b). These factors can influence learning, underscoring the need to control for them when investigating the longitudinal effects of chronic environmental noise on learning. Despite the difficulty, considering the potential long-term consequences and the accumulation of risk factors in exposed children, taking this issue seriously is imperative (Evans, 2004; Klatte et al., 2013).

A final important limitation in current research is the predominant use of homogeneous and continuous noise in experimental studies. However, in real-life, background noise is often intermittent, involving noisy periods, silent pauses, or interruptions, which might be more distracting. The scarcity of research on intermittent noise might be due to its unpredictability, irregular intervals, and complex variations in loudness, making it challenging to record or synthesize and assess its direct effects. Despite this, even in this case, it would be important to analyze the impact of this type of noise.

In Table 2, the main gaps identified in the literature based on the primary results from the analysis of the studies are summarized, along with potential perspectives for new studies aimed at addressing these gaps and advancing knowledge on the subject (see Table 2).

Table 2. Summary of the Main Gaps Identified in the Literature, Primary Results From the Systematic Review, and Potential Perspectives for New Studies.

Research findings	Gaps in the literature	Future directions
Studies examining the impact of noise on Efs have primarily focused on a limited set of EF skills, mainly verbal and non-verbal WM	Lack of studies conducting comprehensive analyses of how noise characteristics interact with various cognitive tasks	Studies investigating the direct impacts of various noise types of noise on attention (not merely treating attention as a variable that might moderate the effect) and on other EFs, such as cognitive flexibility and inhibition
Acute noise appears to have a negative effect when examined in relation to verbal WM or attentional skills	Few experimental studies explore acute noise effects on learning	Experimental studies examining the effects of different types of acute noise on learning tasks such as reading, writing, and arithmetic
Speech noise typically has a negative impact on verbal WM performance, often through the Irrelevant Speech Effect	Almost no study has compared different verbal noise masking types (e.g., single talker, four talkers, multitalker noise)	Research investigating the impact of the number of talkers on informational masking aim to understand how different levels of intelligible speech noise affect children's cognitive abilities
Chronic noise typically has adverse effects on reading skills, impacting both comprehension and reading speed	Scarcity of longitudinal studies on the causal impact of chronic noise exposure on different learning abilities	Studies exploring the longitudinal effects of chronic environmental noise on diverse learning tasks and assessing the potential long-term consequences across different age groups in children
Almost all experimental studies have utilized a uniform and continuous noise	Lack of experimental studies on the effects of real-life background noise	Experimental studies on the effects of noise that is intermittent, unpredictable, with irregular intervals, and complex variations in loudness, which might be more distracting
White noise can enhance cognitive performance by boosting attention, particularly in children experiencing attentional difficulties	Limited research has focused on special needs populations, such as children with hearing loss or attentional deficits	Studies on the effects of different types of noise on children with neurodevelopmental disorders

Conclusion

While the global impact of noise on well-being and cognition is well-documented (Clark & Paunovic, 2018a, 2018b), its specific effects on children's cognitive functioning and learning remain largely underexplored. With this SR we attempted to systematically organize and discuss the research on the cognitive effects of noise in children, highlighting knowledge gaps and directions for future studies. There is agreement among the studies that both acute and chronic noise exposure, from moderate to severe levels, influence children's cognitive and learning performance. The effects of chronic noise could be an area of particular interest for future research, due to their potential long-term consequences, especially considering that children spend most of their daily time in noisy environments. Since primary school children haven't fully developed EFs and learning skills, their capacity to compensate for the effects of noise remains limited. Therefore, noise presents a threat for both their learning progress and overall well-being.

Reducing the impact of noise isn't straightforward. To counter chronic environmental noise like road traffic, structural changes such as creating better acoustic learning spaces or using sound-absorbing panels in classrooms are essential. Yet, this literature review implies that these interventions might not be enough without interventions on classroom noise management strategies. When speech and activity noise disrupt learning, it's crucial to combine improvements in classroom acoustics with behavioral programs teaching noise-management behaviors.

This review finally highlights that noise effects vary based on the individual characteristics of the students in a classroom. Non-speech and speech noise may impact some children differently, with some individuals, e.g., those with attentional problems, potentially benefiting from specific noise types and levels (8; 22). Recognizing the interplay between noise features (e.g., frequency, sound pressure, time distribution) and children's individual characteristics (e.g., neurodevelopmental disorders) is essential. Further research is necessary to fully comprehend this interaction and its implications, representing a new frontier for acoustics and cognitive science researchers.

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Supplemental Material

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Health implications of the rapid rise of data centers in Virginia: an exploratory assessment

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Driven by advances in cloud computing, cryptocurrency, and artificial intelligence, the rapid proliferation of data centers may pose severe human and planetary health risks. This paper, to the best of our knowledge, is the first-of-its-kind assessment of the potential health implications associated with data centers. Here, we examine the case of Virginia's Data Center Alley, the world's largest concentrated data center hub, and argue that data centers can cause public health harms, harms that can be at least partially mitigated through improved planning and design. We assess the health risks associated with data centers, including air pollution, extensive water use, noise pollution, and detrimental land use's risk of disrupting natural ecosystems and community well-being. We also address how rising energy costs can worsen social determinants of health. To mitigate these risks, we recommend transitioning data centers to renewable energy, implementing strict regulations to minimize water consumption, and optimizing site planning with acoustic treatments and green zoning to reduce noise pollution. Additionally, we advocate enforcing responsible site selection and zoning regulations to curb adverse land use changes, equitable energy pricing to alleviate economic burdens, and strengthening health communication for informed public and governmental decision-making, action-oriented advocacy, and policy changes. Finally, we emphasize the need for transdisciplinary research integrating physical sciences, engineering, and public health to quantify specific health outcomes linked to data centers.

KEYWORDS

advocacy, climate change, data centers, public health, sustainable development

Introduction

The surge in demand for computing infrastructure, driven by advancements in cloud services, cryptocurrency, and artificial intelligence, has led to extensive data center construction globally (Masanet et al., 2020; International Energy Agency, 2024). There is a small but growing body of research on societal problems associated with data centers (see Al Kez et al., 2022; Lei et al., 2023) but to the best of our knowledge, research has not yet been done on the human health effects of data centers. Here, we make the case that data centers can cause public health harms, harms that can be at least partially mitigated through improved planning and design.

In this paper, we present evidence arguing that data centers may pose significant health risks, including diseases associated with air pollution from fossil fuel combustion, waterborne illnesses resulting from excessive water usage, and both mental and neurological health concerns related to noise pollution. We further discuss how data center construction drives large-scale land use changes, degrading natural ecosystems and community well-being, and how rising energy costs can worsen social determinants of health. Finally, we emphasize that children, the elderly, and low-wealth groups can be particularly susceptible to the health impacts associated with data centers.

Although data centers are expanding globally, here we focus primarily on Northern Virginia because it is one of the largest concentrations of data centers anywhere in the world, using it as a case study to draw broader public health insights. This area is often referred to as the "Data Center Alley", handling an estimated 70% of the world's internet traffic (Samuelson, 2024). The region's proximity to Washington, D. C., coupled with early investments in fiber-optic networks and energy infrastructure, affordable land, low-cost energy, and minimal natural disaster risks, has made Northern Virginia a prime location for data centers since the 1960s (Kidd, 2023). State policies, such as the 2009 sales tax exemption for data center equipment, have further strengthened Virginia's leadership in the data center industry.

Figure 1 illustrates the geographical distribution and scale of both existing and proposed data centers in Northern Virginia, showing that nearly 80% are located in three counties: Loudoun, Prince William, and Fairfax. Data on existing and proposed data centers suggests that this geographic distribution will only get more concentrated in the region, with data center footprints expected to more than double in the region as more and larger installations go online. Other areas where data centers are currently concentrated include counties surrounding Virginia's capital, Richmond (e.g., Henrico and Hanover counties).

While Virginia's data centers generate economic benefits, which can be an asset in strengthening the region's social determinants of health, it is important to determine whether these gains are equitably distributed or whether they merely exacerbate existing economic and health disparities. Moreover, addressing the subtle yet growing climate threat from data centers, which poses a risk to Virginia's climate progress, is essential. Below, we discuss the potential health implications of data centers related to air pollution, excessive water use, noise pollution, land use changes, and economic burdens on low-income households.

This exploratory assessment draws on peer-reviewed and grey literature published from the early 2000s through 2025, identified through targeted searches of academic databases (Google Scholar, PubMed, Web of Science, and Scopus) using search terms including data centers, digital infrastructure, energy demand, air and water pollution, noise, land use change, climate change, and public health. Given the rapidly evolving nature of data center development and regulation, we also included grey literature such as government and regulatory reports, established environmental organizations reports,

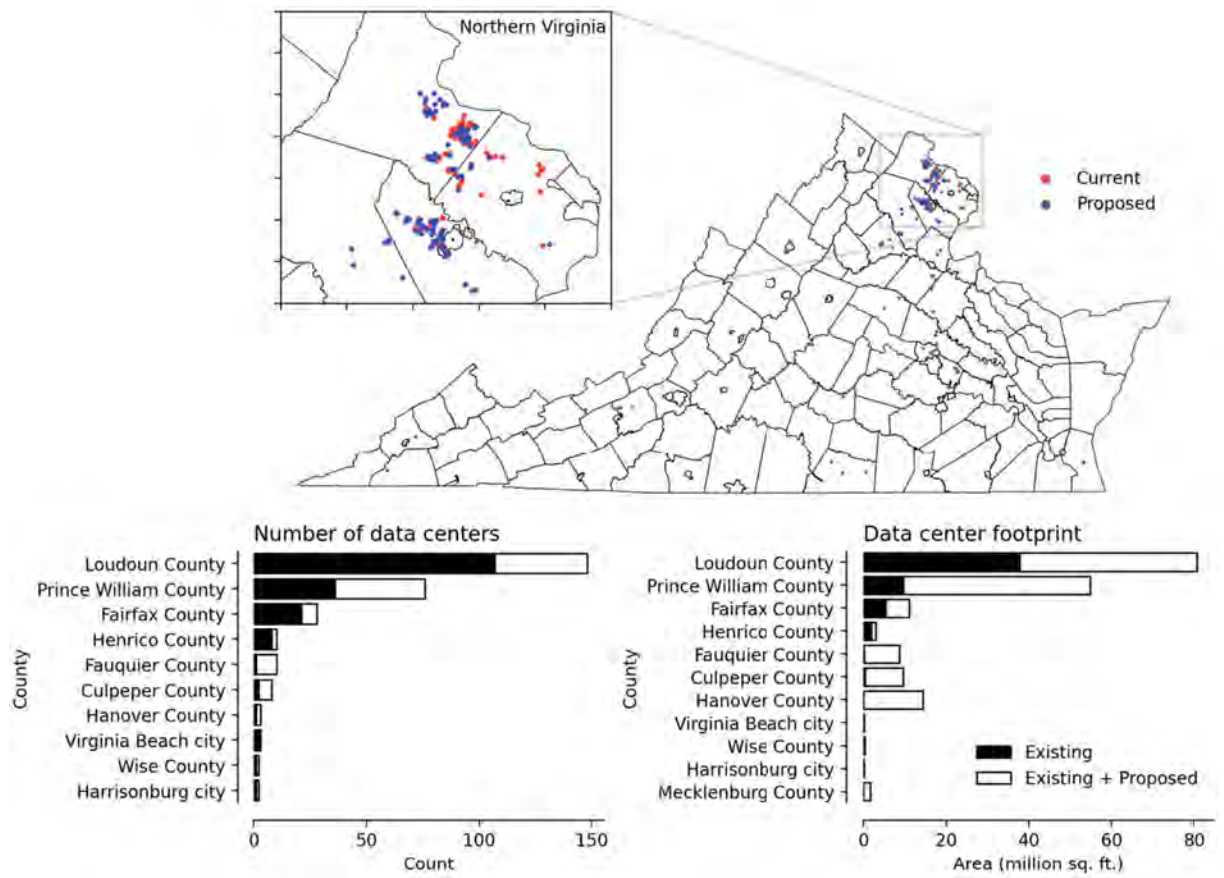

FIGURE 1
Distribution and scale of existing and proposed data centers in Northern Virginia. Data source: Piedmont Environmental Council (2024) (The Piedmont Environmental Council has pulled together this information on existing data center facilities (that they are aware of), along with pending data center proposals they have found on various town and county websites, as well as through various news outlets. It is their best approximation given the information available and is subject to change as more data centers are proposed, approved, or denied), Accessed March 2024.

and coverage from reputable media outlets, which were evaluated based on institutional authorship, transparency of sources, and consistency with peer-reviewed evidence. Sources were selected to synthesize converging evidence across disciplines and to identify plausible health pathways, knowledge gaps, and policy-relevant concerns.

Likely health impacts of data centers

Air pollution

Data center operations increase electricity demand and reliance on fossil fuel–based power generation and backup diesel generators, contributing to increase in air pollutant emissions [Cohen et al., 2017; Joint Legislative Audit and Review Commission (JLARC), 2024]. These emissions may contribute to both short-term exposures (e.g., acute respiratory and cardiovascular effects) and long-term health risks, including chronic disease, adverse reproductive outcomes, and premature mortality (Di et al., 2017; Rajagopalan et al., 2018; Conforti et al., 2018).

Data centers in Virginia are a major source of air pollution attributable to their round-the-clock energy-intensive operations, a critically strained electric grid, and backup diesel generators (Piedmont Environmental Council, 2024). Despite their essential role in the digital economy, data center sites in Virginia consume a substantial portion of the state's electricity, with an estimated power use of 5,050 megawatts [Joint Legislative Audit and Review Commission (JLARC), 2024]. The rising electricity demand from data centers, which accounted for 21% of Virginia's major utility company Dominion Energy's sales in 2022 and is projected to double by 2040 (Piedmont Environmental Council, 2024), drives higher greenhouse gas emissions and air pollution, thereby increasing chronic health risks.

Virginia's electricity generation heavily relies on fossil fuels, with 54% from natural gas and 4% from coal (U.S. Energy Information Administration, 2024b). Virginia imports a significant share of its electricity (36% in 2024), making it the largest net importer in the US, and because much of this power comes from coal-heavy states like West Virginia (where 86% of generation is coal-based), the state's demand shifts pollution burdens across its borders (U.S. Energy Information Administration, 2024a,c). This reliance on fossil fuels, primarily natural gas—which consists of 70–90% methane—contributes to greenhouse gas emissions and air pollutants such as sulfur dioxide, nitrogen oxide (NO_2), particulate matter (PM), and carbon dioxide (CO_2) exacerbating climate change and worsening air quality-related health risks (Cohen et al., 2017; Mailloux et al., 2022; Lelieveld et al., 2019; Vohra et al., 2021). These gaseous and particulate pollution are linked to serious health harms including respiratory and cardiovascular diseases, various cancers, neurological disorders, and conditions such as stroke, dementia, diabetes, and childhood asthma (Lelieveld et al., 2023; Peeples, 2020; Markandya and Wilkinson, 2007; Shah et al., 2015; Wang et al., 2022; Rajagopalan et al., 2018). Moreover, air pollution has been linked to reduced fertility, lower live birth rates, and increased risks of miscarriage and stillbirths, highlighting significant concerns for female reproductive health (Conforti et al., 2018).

Data centers' extensive use of diesel generators causes air pollution which may further exacerbate the health issues noted above. Virginia's data centers have more than 4,000 backup diesel generators. Used primarily during power outages, which Federal Energy Regulatory Commission (FERC) estimates to have been 6.78 h per year for the average customer in Virginia in 2022 and 2023, these generators also undergo routine testing 10–30 min per month [Joint Legislative Audit and Review Commission (JLARC), 2024], yielding an estimated number of hours in use statewide of approximately 35,000 to 51,000 h.[1] When in use, these diesel generators can emit harmful pollutants like NO2, particulate matter, and carbon monoxide (Tsai et al., 2011; Liu et al., 2005; Liang et al., 2005; Saiyasitpanich et al., 2005). Exposure to these pollutants has been associated with respiratory and cardiovascular diseases and neurological problems, particularly among older adults and children (Hesterberg et al., 2012; Peeples, 2020; Loh et al., 2007; Zhang, 2017).

Moreover, rising temperatures from climate change increase cooling demand and together with the rapid growth of data centers, add additional strain to the grid, raising the likelihood of power outages, particularly during heat waves (Do et al., 2023). Virginia has experienced increasingly frequent and severe heat waves over the past decades, with average summer temperatures rising by nearly 2 °F since 1970 (NOAA National Centers for Environmental information, 2025). Cooling degree-days have increased across all climate divisions in Virginia, rising by 11 to 25 °C days per decade over the past 60 years (First Virginia Climate Assessment, forthcoming 2025), which directly increases summer cooling demand—a key driver of data center energy use (Ruess et al., 2025). In June 2025, a record heat wave caused 828 heat-related emergency visits statewide in 4 days (Natural Resources Defense Council, 2025). The urban heat island effect, particularly pronounced in densely built regions like Northern Virginia, further increases local temperature extremes and cooling demands. These conditions heighten the energy needs of data centers, worsen air quality, and compound cardiovascular and respiratory risks, while also increasing the likelihood of power outages that impact individuals with existing health conditions.

Additionally, the reliance on diesel generators during power outages, particularly by hospitals and data centers, can worsen air pollution, further increasing health risks during these hot periods. Studies have shown that extreme heat can significantly increase cardiovascular mortality and, when combined with high PM 2.5 levels, can also elevate the risk of mortality from myocardial infarction, especially among women and the elderly (Khatana and Groeneveld, 2023; Xu et al., 2023).

Beyond air quality and health effects, data centers are also an emerging driver of climate change. U. S. data centers emitted 105 million tons of CO_2e in 2023–2024, accounting for 2.2% of national emissions (Guidi et al., 2024). While data centers currently account for a smaller share of global emissions than fossil fuel industries, their rapid growth and geographic concentration make them a rising climate and health risk. For perspective, Heede (2013) showed that just 90 fossil fuel producers

1 Calculations are based on an average annual outage of 6.78 h per customer (6.78 × 4,000 = 27,000 h) and aggregate monthly testing of 10–30 min per generator (10–30 min x 12 months x 4,000 generators = 8,000–24,000 h).

are responsible for nearly two-thirds of historic global emissions, underscoring the urgency of addressing emerging sources like data centers.

Water consumption and pollution

Data centers affect health indirectly through intensive water use and wastewater discharge associated with cooling systems, which can strain local water supplies and degrade water quality (Mytton, 2021). These changes can increase risks of water scarcity, waterborne diseases and poor maternal and infant health outcomes, with effects that may intensify over time under drought and climate stress (Currie et al., 2013; Stanke et al., 2013).

Data centers require significant resource consumption, with water playing a crucial role both directly in cooling systems and indirectly through electricity production. Globally, data centers significantly contribute to the water footprint, with projections indicating usage between 4.2 and 6.6 billion cubic meters by 2027—exceeding the annual water consumption of countries like Denmark (Li et al., 2025). In the U. S., they rank among the top 10 industrial water users, consuming roughly 513 million cubic meters in 2018 alone (Siddik et al., 2021). A medium-sized data center (15 megawatts) consumes as much water as three hospitals or two 18-hole golf courses, while hyperscale data centers (100 + megawatts)—the largest and most efficient type of public cloud facilities could use even more (Mytton, 2021; Wren, 2024; Powell, 2024). For perspective, Microsoft's data center used 700,000 liters of water to train GPT-3, while generating just one 100-word email using GPT-4 requires approximately 519 milliliters of water (Verma and Tan, 2024).

In Virginia, these pressures are particularly acute because water is already heavily allocated to thermoelectric power generation, agriculture, public supply, and industrial operations (McCarthy et al., 2022). Rapid growth in the data center sector, a 250% increase in water use over four years, now competes directly with these existing demands, intensifying stress on rivers and groundwater, particularly in warmer months [Sierra Club, n.d.; Joint Legislative Audit and Review Commission (JLARC), 2024]. This proliferation in drought-prone regions is worsening local water scarcity (S&P Global, 2025). Collectively, data centers in Northern Virginia consumed nearly 2 billion gallons (7.57 billion liters) of water in 2023—a 63% increase since 2019—underscoring how this new demand compounds longstanding pressures on Virginia's water system. Adding to these pressures, Virginia has spent much of the past decade in at least "Abnormally Dry" conditions as classified by the U. S. Drought Monitor, further straining already limited water supplies (U.S. Drought Monitor, 2024).

Beyond water quantity, data center cooling systems can affect water quality through the discharge of saline wastewater, or blowdown, from evaporative cooling towers (Siddik et al., 2021; Copley, 2022). Cooling water blowdown contaminants such as sodium, magnesium, sulfate, and potassium can contaminate groundwater supplies, posing serious health risks when their concentrations increase (Soliman et al., 2021). For example, high sulfate levels in groundwater can cause skin irritation and diarrhea, especially in infants (Miao et al., 2011). Exposure to contaminated drinking water during pregnancy has also been associated with adverse fetal outcomes, including low birth weight and preeclampsia (Currie et al., 2013; Thompson et al., 2022).

The reliance on water-scarce basins for data center operations may further worsens health risks, particularly in regions like Virginia, which is already experiencing droughts and water stress due to climate change. Drought conditions reduce water availability and flow, leading to stagnant, warm environments that promote the growth of pathogens, increasing the risk of waterborne diseases such as diarrheal illnesses, eye and ear infections, and *E. coli*, among others (Bell et al., 2018; Stanke et al., 2013). Drought has also been linked to increased wildfire risk, with downstream impacts on cardiovascular and respiratory health among children (Berman et al., 2017). In water-stressed agricultural regions, prolonged drought may additionally contribute to mental health risks, including heightened stress, anxiety, and psychological distress among affected populations (Polain et al., 2011; Berman et al., 2021).

Noise pollution

Continuous operation of cooling systems and generators produces persistent noise exposure near data centers, creating a direct environmental stressor. Short-term effects include sleep disturbance and annoyance, while long-term exposure is associated with cardiovascular, cognitive, and mental health impacts (Babisch et al., 2013; Thompson et al., 2022).

Data centers contribute to local noise pollution through their cooling systems, backup diesel generators, and other machinery (Judge, 2022). Operating 24/7, data centers in Virginia generate a persistent humming noise, described as an industrial-scale 'drone' or 'hum' similar to amplified house air conditioning, with levels ranging between 40 and 59 decibels [Joint Legislative Audit and Review Commission (JLARC), 2024]. While the U. S. Environmental Protection Agency (EPA) recommends a 24-h average outdoor noise limit of 55 dBA (day–night average) or 45 dBA indoors to protect public health (U.S. Environmental Protection Agency, 1974), data center operations in residential areas often approach or exceed these thresholds.

The health impacts of noise pollution include long-term risks such as heart disease, permanent hearing loss, and tinnitus; chronic effects such as hypertension and endocrine disruption; and acute effects like decreased sleep quality and temporary hearing changes (Babisch et al., 2013; Hammer et al., 2014). Noise pollution has also been linked with an increase in mental health concerns, such as stress-related disorders and increased annoyance, particularly in sensitive individuals (Meerlo et al., 2008; Sandrock et al., 2008). Past research has shown that noise pollution is particularly concerning for children, as exposure can lead to poor cognition (Thompson et al., 2022). For instance, studies have found that children in noisy environments, defined by the U. S. EPA as chronic exposure above 55 dBA (day–night average), exhibit poor school performance, increased stress, and behavioral issues, with noise pollution also being linked to decreased learning, lower reading comprehension, and concentration deficits (Lercher et al., 2003; Stansfeld and Clark, 2015). For children residing near data centers, the constant noise from 24/7 operations could further exacerbate these developmental and cognitive risks, potentially impacting their long-term health outcomes.

Land use changes

Large-scale land conversion for data center development alters local ecosystems and built environments, indirectly affecting health through loss of green space, increased heat exposure, air pollution, and psychosocial stress. These effects are cumulative and long-term, with disproportionate impacts on rural and historically marginalized communities (Aerts et al., 2018; Johnson-Jennings et al., 2020).

Data centers require vast amounts of land, often converting areas near natural green spaces and agricultural lands into data center sites. Data from the Piedmont Environmental Council (2024) show that existing data centers in Northen Virginia currently occupy about 6,200 acres of land, while proposed projects would add nearly 21,000 acres, more than tripling the current footprint in Northern Virginia alone, where roughly 80% of data centers are located.

Our analysis of existing and proposed data centers in Northern Virginia found that the 152 proposed facilities are, on average, five times larger than the existing 191 data centers. The rapid data center expansions in Northern Virginia are increasingly targeting rural land near national parks and agricultural land into industrial zones, posing risks to public health. For example, Prince William County is facing its largest land-use transformation in decades, with developers targeting 2,400 acres of undeveloped land in the Rural Crescent for data center construction. This area contains two federally protected national parks, Prince William Forest National Park and Manassas Battlefield National Park, which together attract over a million visitors annually (Regelbrugge, 2022). Moreover, over 100 additional projects are currently planned in Northern Virginia, collectively adding roughly 180 million square feet of data center space, equivalent in area to 1,000 Walmart Supercenters (Sierra Club, n.d.). Moreover, residents have raised concerns about vehicle traffic from data center construction, citing road damage, congestion, and blocked access for school buses and emergency vehicles [Joint Legislative Audit and Review Commission (JLARC), 2024]. This can increase local air pollution (e.g., particulate matter and diesel exhaust), indirectly contributing to respiratory and cardiovascular health risks, especially among vulnerable populations.

This rapid transformation threatens rural populations, contributing to increased psychological stress, exacerbated by limited healthcare access. The loss of farmland can disrupt local economies and erode cultural and historical ties, particularly for Indigenous people and farmers who see the land as central to their identity and psychological well-being (Johnson-Jennings et al., 2020; Reed and Claunch, 2020; Yazd et al., 2019; Brigance et al., 2018).

Importantly, the proximity of data centers to green spaces degrades ecosystems by replacing vegetation with impervious surfaces, fragmenting habitats, and disrupting hydrology, thus reducing their capacity to filter air, regulate temperature, and sustain biodiversity [Joint Legislative Audit and Review Commission (JLARC), 2024; Nguyen et al., 2021]. Combined with air, water, and noise pollution from data centers, this ecological degradation can weaken green spaces' protective functions and increase health risks in nearby communities. Conversely, green spaces are linked to health benefits by reducing air pollution and the urban heat island effect, encouraging physical activity, and enhancing mental health, contributing to overall better health and increased life expectancy (Nowak et al., 2006; Jones, 2018; Shanahan et al., 2016). For example, increased tree cover has been shown to enhance natural air pollutant absorption, reducing the incidence of respiratory illnesses like asthma, Chronic Obstructive Pulmonary Disease, and cardiovascular diseases, especially among children (Liang et al., 2019; World Health Organization, 2016; Ruokolainen et al., 2015). Past research has also emphasized the importance of green spaces in improving the health of pregnant women and people with existing illnesses (Dzhambov et al., 2014; Ray and Jakubec, 2014). Research also emphasizes that proximity to green spaces is linked to better mental well-being and social support (Wigand et al., 2022; Aerts et al., 2018).

Economic harms and social inequality

Rising electricity demand from data centers places upward pressure on energy prices, indirectly affecting health through increased energy insecurity. Short-term impacts include heat- and cold-related illness due to inadequate household energy access, while long-term effects include chronic stress, food insecurity, and widening health disparities (Ballesteros-Arjona et al., 2022).

While data centers generate notable economic benefits, these gains are often concentrated among a select few, neglecting the broader public. Data centers are significant consumers of electricity, substantially increasing local energy demand and associated costs (Pipkin, 2024). According to Goldman Sachs (2024) Research, the data center's global power demand is projected to grow by 160% by 2030. In Virginia, the current energy need of data centers is estimated at about 5,050 MW of load and 11,000 GWh annually (Howland, 2024). Dominion Energy anticipates that Virginia data centers will be the primary driver of increased energy demand over the next 15 years, forecasting a need for about 13.3 gigawatts by 2038 (Vogelsong, 2024). While these data centers currently pay the full cost of service under existing rate structures, their rising energy demand strains Virginia's grid and could raise typical residential bills by $14–33 per month by 2040 [Joint Legislative Audit and Review Commission (JLARC), 2024]. Wholesale electricity prices near major data center hubs have already increased sharply, rising by up to 267% over the past 5 years (Bloomberg News, 2025). These rising energy costs disproportionately affect lower-income households and marginalized communities, exacerbating existing social inequality and health disparities (Ballesteros-Arjona et al., 2022).

Past studies have shown that energy poverty forces vulnerable families to choose between paying for energy and meeting essential needs such as food, healthcare, and education (Pitt et al., 2022; Riva et al., 2023; Harrington et al., 2005). Because climate change is increasing the frequency of hot days, there is also a rising demand for residential cooling systems like air conditioning units (Colelli et al., 2023; Sherman et al., 2022). Rising energy costs may prevent low-income households from accessing adequate cooling, raising the risk of heat-related illnesses, such as heat exhaustion and heat stroke, and worsening pre-existing conditions (Pitt et al., 2022; Hernández, 2013). Moreover, some low-income families may prioritize cooling units over purchasing healthy food, resulting in malnutrition and food insecurity, particularly among children, which can negatively affect their physical growth, cognitive development, and academic performance (Frank et al., 2006; Cook et al., 2008).

Conversely, on colder days, inadequate heating can increase health risks such as respiratory conditions and cardiovascular stress, including heart attacks and strokes (Thomson et al., 2017). Elevated energy costs can also contribute to poor mental health among adults, leading to increased anxiety, stress, and depression (Harrington et al., 2005; Oliveras et al., 2020). Therefore, addressing the rising energy demands and costs associated with data centers is critical to mitigating social inequality and safeguarding the health and well-being of vulnerable communities (Figure 2).

Potential strategies to mitigate the health harms of data centers

The rapid expansion of data centers, fueled by the rising demand for digital infrastructure, poses serious health risks that require coordinated mitigation across energy, water, noise, land use, governance and communication domains. The strategies below are organized by thematic risk pathways identified earlier in the paper and distinguish between policy-level, industry-level, and community-level interventions.

Energy-related strategies (policy and industry level)

Transitioning from fossil fuels to renewable energy for data centers can substantially reduce air pollution and related health issues, as well as lower energy costs. Ortiz et al. (2023) estimate that shifting to renewables for electricity production in Virginia could prevent deaths, reduce hospital admissions, decrease work-loss days, and save up to $350 million annually in health costs by 2045. Several technology companies have already demonstrated the feasibility of such transitions. For example, Microsoft's Project Natick tested underwater data centers powered by offshore renewables, showing improved reliability and reduced environmental footprint (Roach, 2020). In 2024, Google powered its data centers with 100% renewables and added 2.5 GW of clean energy, cutting emissions by 12% despite a 27% rise in electricity use (Google, 2024). These examples highlight the potential for cleaner and healthier digital infrastructure.

Water use and water quality strategies (policy and industry level)

Beyond cutting emissions, reducing data centers' water consumption and water contamination is critical to mitigating public health. Using non-potable water, like Amazon's use of recycled cooling water in Virginia, can ease pressure on drinking water supplies. Targeted cooling methods, such as shifting from whole-room to focused server-row cooling, can cut water use and boost energy

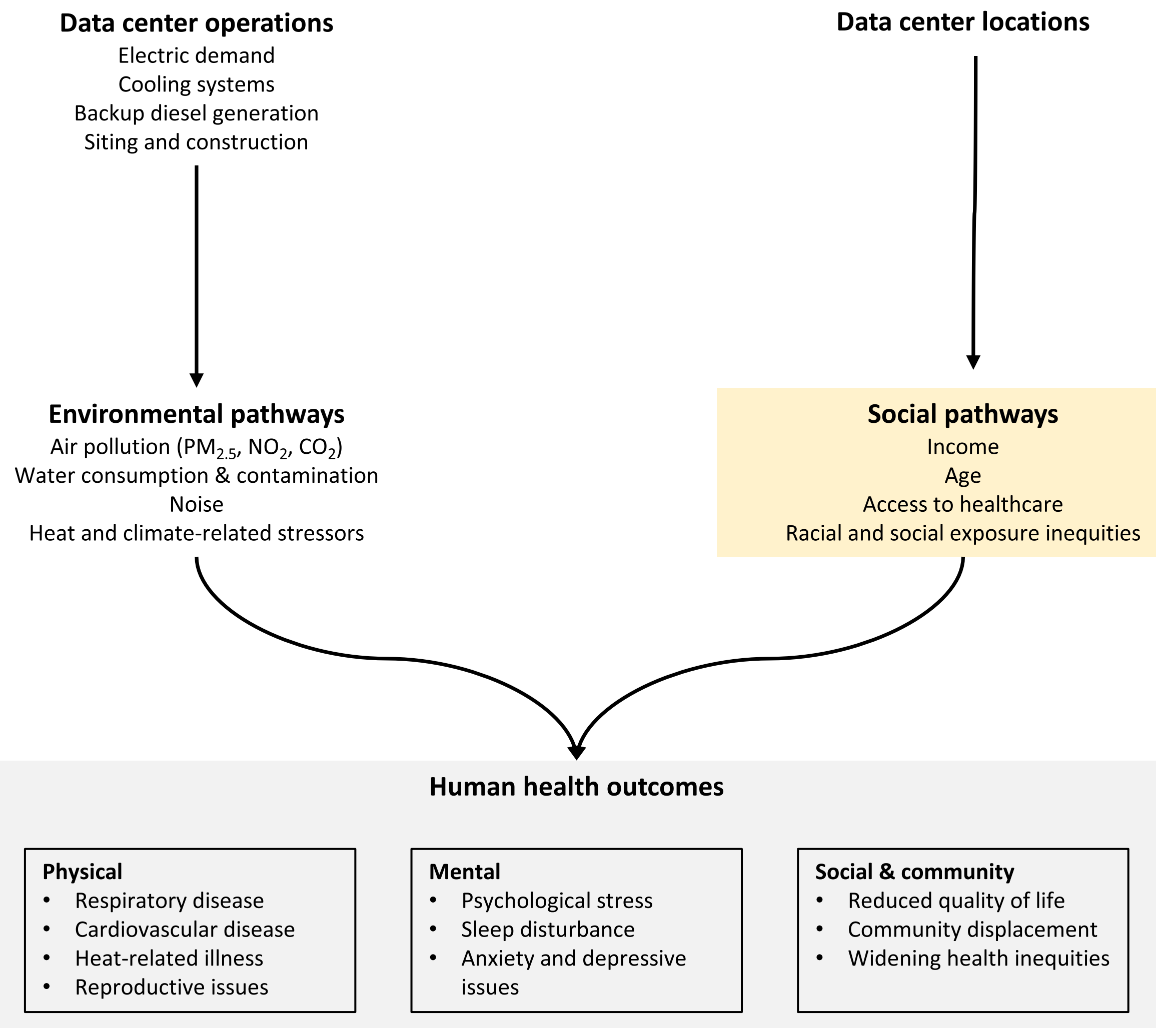

FIGURE 2
Conceptual pathways linking data center operations to human health outcomes.

efficiency by 29% (Moazamigoodarzi et al., 2019). Advanced water recycling and filtration, such as nanofiltration and reverse osmosis, can prevent contamination (see Envirogen, 2023). Moreover, to drive industry-wide change, local governments should enforce water limits during droughts and mandate data centers to adopt alternative cooling methods, such as air cooling, closed-loop systems, or hybrid models with water-side economizers to minimize freshwater dependence and reduce water contamination health risks (Silva-Llanca et al., 2023; Wang et al., 2018). Currently, however, Virginia data centers are not subject to direct regulations on their energy efficiency, emissions, or water use, relying only on general air, stormwater, and wetland permits [Joint Legislative Audit and Review Commission (JLARC), 2024].

Noise and land-use strategies (policy and community level)

Further, mitigating noise pollution is essential, especially in residential areas near data centers. Effective strategies can include locating data centers away from densely populated regions and implementing noise reduction measures such as acoustic treatments and green zoning. Proactive site selection and thoughtful design, considering urban layout and building density, can significantly reduce noise-related health issues (Chan, 2023; Dzhambov and Dimitrova, 2014). For example, a Leesburg Virginia data center reduced noise pollution by re-engineering fan mounts and cutting low-frequency tonal noise by 20% (Compass Datacenters, 2024). Additionally, to limit adverse impacts from land use changes, policymakers should mandate responsible site selection and enforce zoning regulations that prioritize building data centers on existing industrial sites. Engaging local communities through public hearings and transparent decision-making processes can also help address residents' concerns about environmental and health consequences.

Equity and governance strategies (policy level)

Moreover, rising energy costs associated with data center operations disproportionately burden low-income households. When demand exceeds supply, Virginia follows PJM (originally the Pennsylvania–New Jersey–Maryland Interconnection) curtailment rules prioritizing homes and critical services, but no current policy requires data centers to switch to backup power [Joint Legislative Audit and Review Commission (JLARC), 2024], increasing the risk of AC interruptions and related health issues during heat waves for heat-sensitive people. Policymakers should also establish equitable energy pricing by introducing a dedicated data center rate class to shield vulnerable communities from escalating costs. Utility rates, which are currently adjusted every one to two years, need to be revised more frequently to accurately reflect cost growth [Joint Legislative Audit and Review Commission (JLARC), 2024]. Promoting a diversified energy portfolio, such as integrating renewable energy sources can help stabilize electricity prices and reduce dependency on fossil fuels. Additionally, local governments should mandate Community Benefit Agreements to ensure economic benefits from data centers directly support vulnerable populations through infrastructure enhancements, workforce training, and community reinvestment.

Health communication and public engagement strategies (policy and community level)

Finally, raising awareness about the health impacts of data centers is crucial for informed public and governmental decision-making. While community opposition to data centers, often labeled as NIMBYism (Not in My Backyard), frequently centers around concerns about noise, air and water pollution, these concerns reflect legitimate public health risks that demand policy attention (see Paullin, 2025; Paddison and Marsh, 2025). Through strategic health communication, public understanding can be improved, and government action encouraged toward health-focused regulation and more sustainable data center practices. Importantly, engaging trusted stakeholders, such as healthcare professionals, policymakers, and other opinion leaders, is key to this effort (Maibach et al., 2007; Campbell et al., 2025). Primary care doctors, trusted by 69% of American voters for information on global warming (Campbell et al., 2023), are particularly well-positioned to address public concerns about data centers, which raise similar health risks. Simple, clear, and repeated messaging from physicians and other health professionals can build credibility, support action-oriented advocacy, and help drive policy change (Maibach et al., 2014).

Limitations and possible future research directions

While this paper underscores the substantial health risks associated with data centers, it is primarily an exploratory assessment. As such, some limitations should be acknowledged.

First, there is the lack of data center specific epidemiological evidence directly linking data center operations to measured health outcomes. Most existing research examines related environmental exposures, such as air pollution, water use, noise, and heat, without attributing data centers as a distinct source. Second, attributing observed health impacts specifically to data centers is challenging in regions such as Northern Virginia, where multiple industrial, transportation, and power-generation sources coexist. Disentangling data center related exposures from other regional contributors requires high-resolution environmental monitoring and spatially explicit exposure assessment, which remains limited given the novelty of data centers as a public health research domain.

Third, this review also relies on grey literature, reflecting the emerging nature of the topic and the current scarcity of peer-reviewed studies focused explicitly on data centers and health impacts. Finally, this assessment is conceptual rather than quantitative and identifies plausible exposure pathways and health risks without estimating effect sizes or population-level disease burdens.

Future research should conduct quantitative, interdisciplinary studies that integrate physical sciences, engineering, and public health to directly measure emissions, exposures, and health outcomes linked to data center operations. Such work could assess pollutant emissions from increased electricity demand and their respiratory and cardiovascular impacts, as well as unresolved questions related to water demand, regional water management, noise exposure, and climate-related environmental and health effects. Moreover, expanding analyses beyond Virginia to other regions experiencing rapid data center growth would enable comparative assessment across regulatory and geographic contexts and help refine mitigation strategies. In addition, future studies should examine the role of trusted opinion leaders such as healthcare professionals, policymakers, and government officials and effective communication strategies, including message framing, to enhance issue awareness and positively influence public attitudes and behaviors.

Conclusion

As data centers expand, both existing and proposed facilities pose significant health and environmental challenges that demand urgent action. Policymakers must mitigate harms from operational data centers by enforcing stricter environmental regulations, monitoring emissions, and mandating mitigation measures to protect surrounding communities. Transparency is essential. Residents have the right to know the risks associated with data centers and should be actively informed about industry practices. Conversely, developers must engage the public to address their concerns, especially as opposition grows under NIMBY movements. Moreover, for proposed new data centers, public input must guide decision-making—do residents want them, and if so, under what conditions? Developers must adhere to clear design and operational safeguards, including renewable energy integration, water conservation, noise pollution control measures, and responsible land siting. By prioritizing sustainability, data centers can achieve responsible growth without compromising public health.

Author contributions

NG: Conceptualization, Writing – original draft, Writing – review & editing. LO: Conceptualization, Visualization, Writing – review & editing. EM: Conceptualization, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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RESEARCH

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Effect of low-frequency noise exposure on cognitive function: a systematic review and meta-analysis

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Abstract

Background Low-frequency noise may cause changes in cognitive function. However, there is no established consensus on the effect of low-frequency noise on cognitive function. Therefore, this systematic review and meta-analysis aimed to explore the relationship between low-frequency noise exposure and cognitive function.

Methods We conducted a systematic review and identified original studies written in English on low-frequency noise and cognition published before December 2022 using the PsycINFO, PubMed, Medline, and Web of Science databases. The risk of bias was evaluated according to established guidelines. A random-effects meta-analysis was performed where appropriate. To explore the association between low-frequency noise exposure and cognitive function, we reviewed eight relevant studies. These studies covered cognitive functions grouped into four domains: attention, executive function, memory, and higher-order cognitive functions. The data extraction process was followed by a random-effects meta-analysis for each domain, which allowed us to quantify the overall effect.

Results Our analysis of the selected studies suggested that interventions involving low-frequency noise only had a negative impact on higher-order cognitive functions ($Z = 2.42$, $p = 0.02$), with a standardized mean difference of -0.37 (95% confidence interval: -0.67, -0.07). A moderate level of heterogeneity was observed among studies ($p = 0.24$, $I^2 = 29\%$, $Tau^2 = 0.03$).

Conclusions Our study findings suggest that low-frequency noise can negatively impact higher-order cognitive functions, such as logical reasoning, mathematical calculation, and data processing. Therefore, it becomes important to consider the potential negative consequences of low-frequency noise in everyday situations, and proactive measures should be taken to address this issue and mitigate the associated potential adverse outcomes.

Keywords Low-frequency noise, Noise pollution, Cognition, Higher-order functions, Meta-analysis, Systematic review

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Background

Noise is a well-known environmental stressor that can negatively affect physiological, psychological, and behavioral processes [1, 2], making noise pollution a significant global public health concern. In the United States alone, over a quarter of the workers have been negatively impacted by noise. Furthermore, in its 2020 environmental noise report, the European Environment Agency stated that more than 22 million individuals were adversely affected by noise [3]. Low-frequency noise (LFN) refers to a type of environmental noise characterized by sound waves below 200 Hz. It is considered a distinctive environmental noise issue that affects many households [4]. The sources of LFN can be both natural, including wind, thunder, lightning, waves, earthquakes, and volcanic eruptions, and artificial, including life-related noise (e.g., air conditioning, power distribution equipment, elevators, and fans), traffic noise (e.g., railways and aviation), industrial enterprise noise (e.g., substations, wind farms, and converter stations), and construction noise (e.g., piling and decoration). As LFN becomes more prominent, its effects on humans intensify [5]. Studies have demonstrated the negative effect of LFN on the circulatory, endocrine, and nervous systems of the human body as well as on learning and social behavior [6, 7]. The impact of LFN can often be masked by medium and high-frequency noises, leading to people being less aware of the effects of LFN. Moreover, environmental noise measurements typically involve A-weighting, which significantly attenuates low-frequency components, potentially resulting in individuals being strongly disturbed by LFN, even when measurement values are within the standard limits [8]. The World Health Organization has also emphasized the detrimental effects of LFN for the first time in their *Guidelines for Community Noise* [9]. These recommendations about LFN were developed in the *World Health Organization Night Noise Guidelines for Europe* [10], and the noise guidelines are constantly improving over time [11, 12]. According to another review, it was reported that about 10% of people lived near infrasound or LFN sources, causing diseases of the central nervous system. LFN in the daily environment constitutes a problem that requires more research attention [13].

Cognition refers to the abilities related to the acquisition, processing, utilization, and understanding of information, which involves various functions, such as attention, learning, memory, execution, reasoning, and calculation [14]. Cognitive ability is not only a measure of learning capacity but also an important indicator of physical and mental health. Studies have demonstrated that environmental noise can negatively impact cognitive function [15, 16]. The potential causes for these negative impacts include distraction, reduced sleep quality, reduced speech perception ability, elevated psychological stress, discomfort, and learned helplessness [17–20]. Through analysis of brain structure and organization, it was theorized that this change in cognitive function may be related to gray matter decline in cognition-related brain regions such as the cerebellum and angular gyrus [13] and may also be related to the Ca^{2+} mediated apoptosis pathway in the hippocampal neurons [21].

Previous studies have examined the association between environmental noise and cognitive function, although most studies have included traffic noise rather than LFN as an independent exposure factor for their analysis and research [15, 16]. Some scholars propose that the adverse effects of noise can be attributed to the LFN component, with the rattling or vibrating aspect of LFN potentiating these negative effects [22]. However, research on LFN in occupational environments remains limited, and its negative impacts have not been widely recognized to date [23].

We proposed the question of whether LFN exposure increases the risk of cognitive impairment in humans compared to less LFN exposure. Therefore, this literature review considered LFN as an individual exposure factor. We aimed to systematically analyze and assess the impact of LFN on cognitive function by assessing the risk of bias in the studies and highlighting the primary limitations of existing research. Collectively, these findings can provide a useful theoretical foundation for the development of effective noise protection policies.

Methods

Protocol and registration

This systematic review was conducted according to the PRISMA standards [24] (Additional file 1), and the protocol was pre-registered in the PROSPERO database (ID = CRD42022384598) on December 27, 2022.

Eligibility and inclusion and exclusion criteria

This systematic review was performed in strict accordance with the Population, Exposure, Outcome framework [24]. The PECOS (participants, exposure, control/comparison, outcomes, and study design) statement is described in Table 1. For the literature review, only original research articles were included, whereas review papers, conference records, abstracts, editorials, reports, letters, notes, chapters, books, and theses were excluded. No restrictions were imposed on the publication year or geographic area; however, given the need for accurate understanding of the content and unavailability of translation sources, we only included research papers written in English. We also established specific inclusion criteria

Table 1 The statement of PECOS

Category	Statement
Participants	Human populations across the lifespan
Exposure	Low frequency noise (exposure to noise in a lab to measure concurrent effects on cognition)
Control/Comparison	Persons less exposed
Outcomes	Non-pathological cognitive abilities
Study Design	Experimental study designs

pertaining to the exposure method and outcome of intervention factors as follows:

1) The presence of clear acoustic calibration instructions for noise exposure as an intervention condition, such as the spectral analysis of noise, and the primary component of noise exposure should be explicitly stated as the LFN component.
2) The reporting of cognitive function domains, including performance on neurocognitive tasks, academic skills, overall IQ, measurements of neurodevelopment, and cognitive decline.

Information sources

The literature was sourced from the PsycINFO, PubMed, Medline, and Web of Science databases. Using keywords centered around "low-frequency noise" and "cognition," searches were conducted to identify all published articles relevant to both concepts. The search period spanned from the earliest available date in each database until December 16, 2022. The complete search strategy for each database can be found in Additional file 2.

Study selection

The selected studies bibliography was created using the NoteExpress reference management software. After consolidating the literature and removing duplicates, two authors independently reviewed the literature based on the inclusion criteria. Initial screening involved reviewing the titles and abstracts of all articles, followed by screening the full text. Any discrepancies or uncertainties regarding eligibility or information extracted were resolved through discussion or consultation with other authors. If more detailed information was required from the original article, the authors were contacted for a joint decision on the inclusion or exclusion of the article.

Data collection process

Data were independently collected by the first author using a standardized data extraction table, primarily including data, such as article's authors, publication year, study field, research design, noise type and assessment, results, measurements, adjustments, and effect sizes reported. A second researcher reviewed all the extracted data, and discrepancies were resolved through discussion. All reviewers and data extractors have received unified training and learned about the use of the Revised Cochrane risk of bias tool for randomized trials (RoB 2) [25]. Missing data were obtained by contacting the corresponding authors through email. When the data could not be used directly for analysis, corresponding formulas were applied for data conversion, and subgroup data were reasonably combined. For example, in the study of Belojević G et al. [26], participants were classified based on noise sensitivity, but in other articles, study cohorts were randomly selected from the entire population. Therefore, we merged the three subgroups. First, we merged the two subgroups with medium and low sensitivity to noise, and then we merged the obtained data with the subgroup with high sensitivity to noise to obtain the effective data. The specific extraction and conversion of raw data can be found in Additional file 3.

Data characteristics

Data were extracted from all included articles based on the following four characteristics: 1) intervention and control measures, including the intensity and type of LFN and whether the control group was less exposed; 2) basic subject information, including sample size, age range, and gender differences; 3) experimental design methods, including randomization methods, blinding, within/between-subject designs, and other methods; 4) extraction of continuous variable data, including the mean, standard deviation, and sample size of each group. If the original text did not provide corresponding means or standard deviations, other convertible statistical data, including standard errors, 95% confidence intervals (CIs), and t- or *p*-values, were extracted.

Risk of bias and quality of evidence assessment

Two authors independently assessed the risk of bias in the studies using the RoB 2 for randomized trials [27]. This tool assessed potential threats to the internal validity of randomized controlled trials across six domains of bias: randomization process, deviations from the intended interventions, missing outcome data, measurement of outcomes, selection of the reported result, and overall bias. The possible risk-of-bias judgments for each domain comprised a low risk of bias, some concerns regarding bias, and a high risk of bias [28, 29]. The individual and overall bias risks were strictly evaluated based on the guidelines provided by RoB 2 [30]. Any discrepancies were resolved through discussion or consultation with a third author. We further evaluated the overall quality of evidence and strength of evidence assessments for each outcome using the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) guidelines. The starting level of the quality of evidence was determined according to the study design. This initial level was then increased or decreased considering several factors. Factors that lower the confidence of evidence were: risk of bias, inconsistency of results, indirectness of evidence, imprecision, publication bias, and number of studies. In contrast, a dose–response gradient, a large magnitude of effect, and confounding that underestimate the associations can increase confidence [31].

Summary and synthesis of results and meta-analysis

Due to systematic or random errors, the studies included in the meta-analysis may produce results that deviate from the real population parameters. The purpose of integrating these results into the meta-analysis is to generate estimates that are closer to the real population parameters by minimizing these errors in the study. Meta analysis models are mainly divided into conventional fixed effects and random effects models [32], among which there are also inverse variations, quality effects, and random effects estimators that are used to reduce these errors as much as possible, but there is still a controversy about the most effective estimator [33]. If heterogeneity is expected between relevant research results, a random effects model is usually preferred for analysis [34]. This model handles heterogeneity between data by increasing the weight of large sample data and reducing the weight of large sample data. Although this method carries certain risks, considering the variations in noise intervention, outcome measurement, and target populations across the included studies, a random effects model was still adopted to obtain more conservative results [35, 36]. Using RevMan software, the standardized mean difference (SMD), 95% CI, and *p*-value for different cognitive tasks were calculated. The Q statistic was used to examine the heterogeneity of study results, with a *p*-value of <0.05 indicating heterogeneity across studies. Additionally, the I^2 statistic was utilized to quantify the impact of heterogeneity. Low, moderate, and high heterogeneity were represented by an $I^2 \leq 25\%$, 25%–75%, and $\geq 75\%$, respectively. Heterogeneity was generally considered acceptable if I^2 did not exceed 50% [37, 38].

Results

Study selection

This study included a total of eight original randomized control studies from five different countries, with three articles from Sweden and two from Iran. The specific selection process is shown in Fig. 1. The exclusion reasons for 42 full-text articles can be found in Additional file 4.

Study characteristics

In this study, cognitive function assessment was further classified into four domains: attention, executive function, memory, and higher-order cognitive functions [38]. Detailed information on the classification of functions in each included study as well as in-depth descriptions of LFN are outlined in Table 2.

Risk of bias and quality of evidence assessment

Risk of bias assessment conducted by two authors revealed a moderate risk of overall bias in the included studies quality. In terms of overall evaluation, three studies were considered to have a low risk of bias, whereas five were considered to have an uncertain risk of bias. Major uncertainties were noted in the methods of random assignment and selective reporting of study results. The risk of bias in different domains, both in terms of percentages and summary, is shown in Fig. 2. Detailed assessment data on the risk of bias can be found in Additional file 5. The GRADE system provided information about the certainty of the conclusions and strength of evidence. All estimates were of low or very low quality and the decisions made and reasons for these decisions are specified in Additional file 6.

Impact of LFN exposure on cognitive function

From the perspective of cognitive psychology, cognitive function can be divided into basic and higher-order cognitive functions. Basic cognitive functions include attention, execution, and memory, while higher-order cognitive functions include textual reasoning, decision-making ability, and innovation [39, 40]. Compared to basic cognitive function, in the process of higher-order cognitive function, more brain regions utilize more resources, with the prefrontal cortex and cerebellum playing a core role [41, 42]. For analysis, we subdivided cognitive functions into four domains as mentioned above. The results for each domain are described as follows:

Impact of LFN exposure on attentional functioning

Among the eight included studies, five involved the cognitive function domain of attention. Figure 3 shows high heterogeneity among the studies ($p<0.001$, $I^2=91\%$, $Tau^2=0.56$). A random model was utilized for the meta-analysis, revealing no statistically significant impact of LFN intervention on changes in attention levels ($Z=0.13$, $p=0.90$), with the SMD being -0.05 (95% CI: -0.75, 0.66).

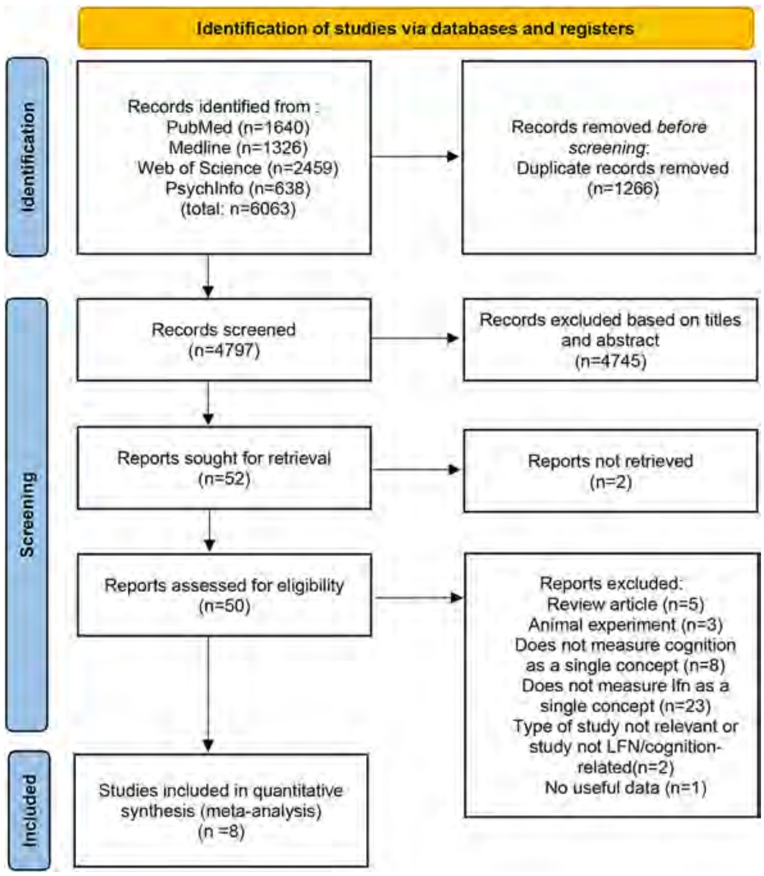

Fig. 1 PRISMA-style flowchart of the study selection process

Impact of LFN exposure on executive functioning
Seven of the eight included studies evaluated executive functioning and were analyzed as shown in Fig. 4. The studies exhibited no heterogeneity ($p=0.58$, $I^2=0\%$, $Tau^2=0.00$). A random-effects model was employed for the meta-analysis, and results revealed that the impact of LFN intervention on changes in attention levels was not statistically significant ($Z=0.76$, $p=0.45$), with an SMD of -0.06 (95%CI: -0.22, 0.10).

Impact of LFN exposure on memory
Four of the eight included studies were related to memory and analyzed as shown in Fig. 5. The studies demonstrated no heterogeneity ($p=0.90$, $I^2=0\%$, $Tau^2=0.00$). A random-effects model was employed for meta-analysis, revealing that the impact of LFN intervention on changes in attention levels was not statistically significant ($Z=0.60$, $p=0.55$) and demonstrating an SMD of -0.09 (95% CI: -0.38, 0.20).

Impact of LFN exposure on higher-order functions
Four of the eight included studies discussed higher-order functions and were subsequently analyzed, as shown in Fig. 6. The studies demonstrated moderate heterogeneity ($p=0.24$, $I^2=29\%$, $Tau^2=0.03$). A random-effects model was utilized for the meta-analysis, indicating that LFN intervention had a negative impact on higher-order cognitive functions, with this difference being statistically significant ($Z=2.42$, $p=0.02$), and an SMD of -0.37 (95% CI: -0.67, -0.07).

Discussion
Summary of evidence
Noise is a serious global public health problem that deserves our attention for its impact on human life and health. Our initial literature search revealed numerous studies on noise and the relationship between noise and cognitive functions. Nevertheless, most of these studies primarily focused on environmental noise, traffic noise, or medium- to high- frequency noise in a broader sense [43–45]. The volume of studies specifically addressing LFN was notably limited, and views on the impact of LFN on cognitive functions were diverse. Some studies have suggested that LFN exposure negatively affects cognitive functions [46–49], whereas others have suggested no such effect [13]. Some even proposed that LFN

Table 2 Descriptive characteristics of studies

Reference	Author	Year	Sample	Details of Intervention	Type of LFN	Cognitive Domain	Cognitive Tasks	Details of Tasks	Std.Mean Difference (95%CI)
Hearing, communication and cognition in low-frequency noise from armoured vehicles	Nakashima, Ann; Abel, Sharon; Duncan, Matthew; Smith, David	2007	*n* = 36; age range: 18–55	The subjects were tested with the ears unoccluded and while wearing a David Clark headset (H10-76XL) in both passive and ANR modes (referred to as "ANR Off" and "ANR On," respectively)	The LFN (hereafter referred to as vehicle noise) was recorded near the ear of the crew commander while standing with his upper body through the hatch of a LAV III. The vehicle was traveling on a highway at approximately 80 km/h	Attentional functioning	Four-choice serial reaction time (SRT)	For the SRT task, one of four probe letters was presented on the screen (P, G, L and S), and the subject pressed the corresponding response button as quickly and accurately as possible	1.09 (0.22,1.96)
						Executive functioning	Mental addition (MA)	The MA task required the subjects to add a random sequence of eight numbers (between 1 and 16) that were presented one by one on the computer screen	-0.05 (-0.85,0.75)
						Memory	Detection of repeated numbers (DRN)	In the DRN task, a series of three-digit numbers were flashed on the screen at a rate of 2/s. The subjects pressed a button when a three-digit number was repeated	0.11 (-0.69,0.91)
						Higher-order functions	A logical reasoning task (LRT)	For the LRT, a pair of letters was shown at the top of the screen (A B or B A) and a statement showing the spatial arrangement of letters was shown below, e.g., "B does not follow A." The subjects responded by indicating whether the statement was "true" or "false."	-0.79 (-1.62,0.05)
A longitudinal, randomized experimental pilot study to investigate the effects of airborne infrasound on human mental health, cognition, and brain structure	Ascone, L; Kling, C; Wieczorek, J; Koch, C; K¨^{1}hn, S	2021	*n* = 38; age mean: 19.76	Six sources were assembled in total, three fully functional sources for the verum group and three dummy sources for the placebo group. The sources were designed to be installed by the setup team in the participants bedroom and then to work for several weeks autonomously and reliably. The main components were a frequency generator, producing a 6 Hz sinusoidal tone, an amplifier,a loudspeaker, and a 26 m flexible tube attached to the speake	The IS sources were configured in such a way that they would emit a steady SPL between 80 and 90 dB (6 Hz frequency) for eight hours during the participant's self-reported habitual sleep (bed) time interval	Attentional functioning	Alertness	Concerning alertness, tonic and phasic alertness can be differentiated. Tonic arousal is a good proxy for wakefulness, where the participant is in a state of willfully maintaining his or her attention and accordingly responds quickly to an upcoming event	-0.39 (-1.05,0.27)
						Executive functioning	Go-nogo	Concerning alertness, tonic and phasic alertness can be differentiated. Tonic arousal is a good proxy for wakefulness, where the participant is in a state of willfully maintaining his or her attention and accordingly responds quickly to an upcoming event	-0.57 (-1.24,0.09)
						Memory	Sustained attention	Sustained attention refers to the capacity to concentrate on a routine task for a longer period of time (15 min in the case of the test)	0.01 (-0.63,0.65)
						Higher-order functions	Incompatibility	Incompatibility effects occur in conflict situations, where divergent information generates a conflict in reaction tendencies	-0.52 (-1.18,0.14)

Table 2 (continued)

Reference	Author	Year	Sample	Details of Intervention	Type of LFN	Cognitive Domain	Cognitive Tasks	Details of Tasks	Std.Mean Difference (95%CI)
Effects of noise on mental performance with regard to subjective noise sensitivity	Belojević, G; Ohrström, E; Rylander, R	1992	*n* = 45; age range: 18–32	Three different acoustic conditions were used in the experiments Background laboratory sound of 30 d B(A) Leq (measured at the subjects' seats) constituted a quiet ambient condition, while the recorded motorway noise, continuous and variable, was emitted at two levels: moderate[Leq = 55 d B(A), L 99 = 48.2 d B(A), L = 62 9 d B(A)l and high lLeq = 75 d B(A), L 99 = 68.2 d B(A), L 1 = 82 1 d B(A)]	The spectral analysis of noise showed a dominance of lower frequency components (40–400 Hz) due to the high proportion of heavy vehicles in motorway traffic	Executive functioning	The Mental Arithmetic task (MA)	The Mental Arithmetic task (MA), a test of parallel processing. A set of 15 tasks invovled mental division of two-digit numbers by 6, 7, 8, or 9, with a two-decimal result The efficiency and the depth of mental processing were estimated by the number of correct whole numbers in the results (shallow), one-decimal results (intermediate), a total results (deep), and by the time spent to complete the task	0.21 (-0.20,0.63)
						Memory	The Short-Term Memory task (STM)	On a computer monitor, 25 series of seven consonants, appearing consecutively with a few seconds' pause, were shown to the subjects In addition, 12 words of different semantic categories appeared occasionally during the projection of letters Consonants had to be recalled by order of appearance and registered on a form after each series The subjects were advised to memorize the letters in groups of 3 + 4 in order to avoid the influence of individual strategies in mental performance The words had to be memorized and written only upon completion of the entire test, without attention to their order The performance was measured by the number of errors and by the number of words remembered in the groups of the same semantic category (clustered) The test lasted 25 min	-0.12 (-0.54,0.29)
Effects of road traffic noise and irrelevant speech on children's reading and mathematical performance	Ljung, R; Sörqvist, P; Hygge, S	2009	*n* = 187; age range: 12–13	In the noise conditions, digital recordings of road traffic noise or irrelevant speech were played back through loudspeakers at the front of the classroom. The equivalent sound level (Leq) in the noise conditions was set to 66 dBA 2 m in front of the loudspeakers. The road traffic noise recording was made up of a background of continuous road traffic noise (~ 62 dBA) with superimposed segments of trucks passing by. The peaks in the superimposed segments were at 78 dBA	The dominant frequency range for the road traffic noise (100–300 Hz) was lower than that for the irrelevant speech (500–1500 Hz)	Executive functioning	Reading Test	The test consisted of a four-page story. With regular intervals there was a critical choice point. At these points, three words were presented. Each word was grammatically correct in the phrase in which they occurred, but two of them were wrong in the context. The task was to underline the word that was correct in the context	-0.21 (-0.20,0.63)
						Higher-order functions	Basic Mathematics	This test consisted of arithmetical and geometrical problems. The arithmetical tasks were division (three problems) and multiplication (three problems). The geometrical problems were naming points in a coordinate system (two problems), understanding of the relationship between fractional expressions and areas of figures (four problems), understanding of the relationship between distance and numerical expressions (two problems), and measuring of distances (two problems)	-0.49 (-0.86,0.12)

Table 2 (continued)

Reference	Author	Year	Sample	Details of Intervention	Type of LFN	Cognitive Domain	Cognitive Tasks	Details of Tasks	Std.Mean Difference (95%CI)
Low frequency noise "pollution" interferes with performance	Persson, Waye K; Bengtsson, J; Kjellberg, A; Benton, S	2001	$n=32$; age mean: 23.3	The sound was produced by four loudspeakers, hidden behind curtains and placed in each comer of the room To amplify the low frequency noise, there was a subwoofer (acebass B2-50) which can reproduce frequencies down to 20 Hz. The background noise from the test chamber ventilation was less than 22 dBA, and the sound pressure levels for frequencies below 160 Hz were below the threshold of normal hearing [ISO389-7:1996]	To obtain the low frequency noise, sound pressure levels in the frequency region of 31.5 to 125 Hz were increased using a digital sound processor system	Memory	Short-time Memory Task	A set of numbers, e.g. 1 2 5 4, was shown on the computer screen. This set was followed by one number, e.g. 7. The subject was to respond, by yes or no, to whether that number was also present among the set of numbers shown earlier. The total response time and total number of correct and false answers were recorded	-0.26 (-0.38,0.20)
The Effect of Road Traffic Noise on Reaction Time	Alimohammadi, I; Zokaei, M; Sandrock, S	2015	$n=80$; college students	At first stage the participants were asked to do the above mentioned RT test in the acoustic room in quiet condition (with background noise of 32.9 dBA) equipped with universal panel of Vienna test system. In second stage case group participants were exposed to traffic noise levels with 72.9 dBA for duration of two hours and then they did the RT test. In this stage, control group participants had been sat in acoustic room for two hours without noise and then they did RT test	In this experimental study, participants were exposed to road traffic noise with level of 72.9 dBA recorded and measured at ninety points in a central parts (that have often heavy traffic) of Tehran, Iran in 2012(31.5–500 Hz). Noise was measured at A– frequency weighting and fast time weighting. During the traffic noise measurement, the traffic noise was recorded by a high quality voice recorder	Attentional functioning	Reaction Time (RT)	Reaction time was measured by RT test from Vienna Test System. Test form S5 was used in this study. This test form assess reaction time (split into reaction and motor time) in response to simple and complex visual or acoustic signals	0.46 (-0.02,0.90)
						Executive functioning	Movement Time	The mechanical response movement consists either of two visual stimuli (yellow and red lights) or a visual and an acoustic stimulus (yellow light and tone at 2000 Hz). The respondents are instructed to respond less than 2 s otherwise the alternative signals are appeared. The time from the presentation stimuli on the monitor to taking index finger from golden button was considered as movement time	-0.06 (-0.50,0.38)

Table 2 (continued)

Reference	Author	Year	Sample	Details of Intervention	Type of LFN	Cognitive Domain	Cognitive Tasks	Details of Tasks	Std.Mean Difference (95%CI)
The effects of low frequency noise on mental performance and annoyance	Alimohammadi, Iraj; Sandrock, Stephan; Gohari, Mahmoud Reza	2013	$n = 90$; age mean: 23.46	After 30 min, subjects performed Stroop and Cognitrone tests again. During performing tests, there was LFN as well. In other words, the exposure duration to LFN was 30 min plus test performance time. For reducing recall bias, half of the subjects were exposed to 50 dBA at first, and the others were exposed to 70 dBA. At the beginning of each test, sound pressure level was measured near the head of the subject in octave band frequency by B&K (model 2238)	LFN in 50 and 70 dBAwas produced inside the acoustic room by Cool Edit Pro. 2.1. Some of the main sources LFN are computers, printers, and air conditioner systems, usually known as quiet devices. In many administrative offices, the Leq = 50 dB noise can be considered as quiet conditions Meanwhile, based on the authors experience, the noise level in the relatively crowded offices is around Leq = 70 dB	Attentional functioning	Cognitrone Test	Cognitrone test was used for evaluating attention and concentration via identical comparison of figures. In other words, Cognitrone test was applied to assess the attention and concentration through comparison of figures with regards to their congruence	-1.04 (-1.35, -0.73)
						Executive functioning	Stroop Test	Stroop Interference Test is a sensorimotor speed test registering speed performance when reading words and naming colors and the speed performance under color–word interference conditions	-0.03 (-0.32,0.26)
The impact of low-frequency noise on human mental performance	Pawlaczyk-Luszczyniska, Malgorzata; Dudarewicz, Adam; Waszkowska, Malgorzata; Szymczak, Wieslaw; Sliwinska-Kowalska, Mariola	2005	$n = 96$; age range: 19–27	Experiment was performed in a special chamber for psychological tests (6.8 m^2) furnished as an office environment. The preselected subjects, categorized in terms of individual sensitivity to LFN, performed standardized psychological tests during exposure to LFN or reference noise at the same equivalent-continuous A-weighted sound pressure level (SPL) of approx. 50 dB. Each subject carried out tasks once at randomly-assigned exposure conditions	The noise was generated by a set of loudspeakers placed in the corners of the room. Low frequency noise simulated noise occurring in the industrial control rooms. The reference noise was the broadband noise of a predominantly flat frequency character, without dominant low frequency components	Attentional functioning	The Continuous Attention Test (DAUF)	For thirty minutes, rows of triangles are presented on screen under time-critical conditions; the tips of the individual triangles can point either up or down. When a previously determined amount of triangles points down, the subject has to press the reaction button	-0.12 (-0.52,0.28)
						Executive functioning	The Stroop Color-Word Test	It is based on the assumption that reading speed of a color-word is slower, if the word is written in a differently colored font. There is always a delay in naming the color of this word, if color and color-word do not match. This test is used for registration of the color-word interference tendency, i.e. impairment of the reading speed or color recognition due to interfering information. Therefore, it is useful in determining the individual susceptibility to stimulus disturbing mental processes	0.00 (-0.40,0.40)
						Higher-order functions	The Comparing of Names Test	It consists of two columns of words (names). The respondent decides whether couples of words (names) in both columns are exactly the same. This test is designed to measure the ability to see pertinent detail in verbal material	-0.04 (-0.44,0.36)

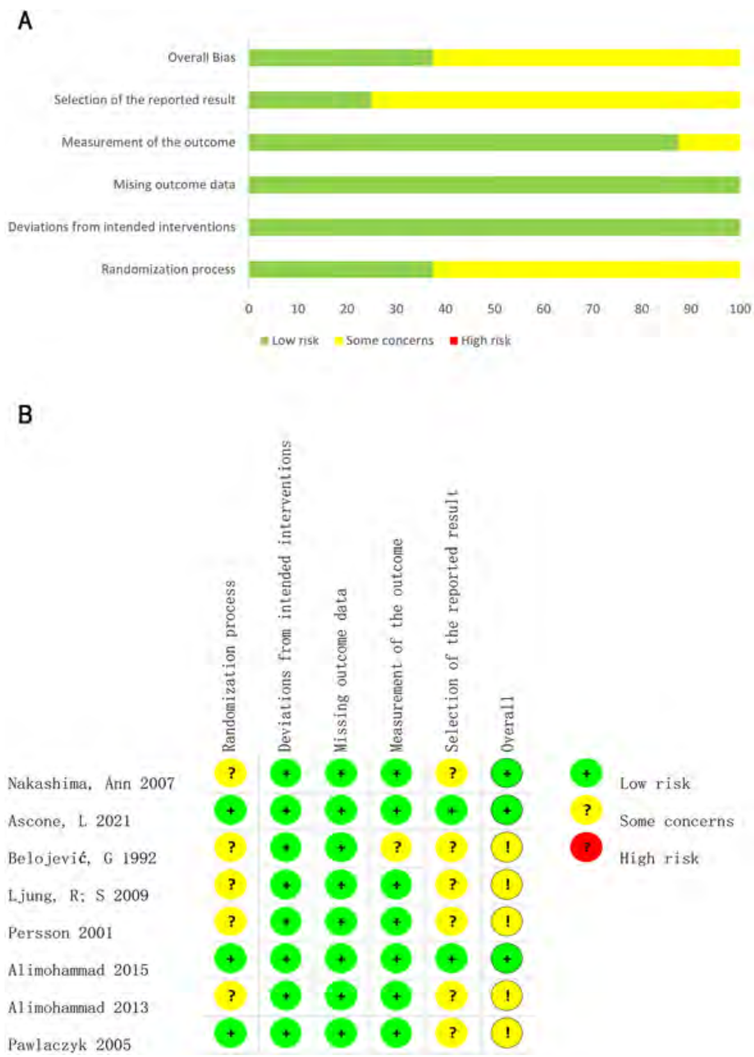

Fig. 2 Risk of Bias of individual studies

exposure can enhance cognitive function [50]. To deepen our understanding of the relationship between LFN and cognitive function, we conducted a meta-analysis.

Cognitive function is a broad and complex concept, therefore, assessing changes in cognitive function from an overall perspective is likely to be one-sided and subjective and could lead to significant heterogeneity issues. To better assess the relationship between LFN exposure and cognitive function, we divided cognitive function into four domains mentioned earlier [39]. In the present study, we evaluated a total of eight studies: five on attention, seven on executive functioning, four on memory, and four on higher-order cognitive functions.

Our meta-analysis concluded that there was a moderate risk of bias and low quality of evidence indicating a negative impact of LFN exposure on higher-order cognitive functions (such as logical reasoning, mathematical calculation, and data processing), with low heterogeneity among the results of related studies. This suggests that responses to LFN within the domain of higher-order cognitive functions are relatively consistent. Previous studies have demonstrated that low-frequency traffic noise slows down reading speed and negatively impacts performance in mathematical tasks [48] and that LFN can reduce mental arithmetic test accuracy [47]. Gao et al. [51] observed a significant longitudinal negative correlation between traffic noise exposure and mathematical performance in cognitive testing. We have demonstrated in a previous study that participants exposed to LFN experience higher levels of cognitive load [52]. Further, LFN exposure does not significantly change basic cognitive functions, such as attention, executive function, and memory. There was

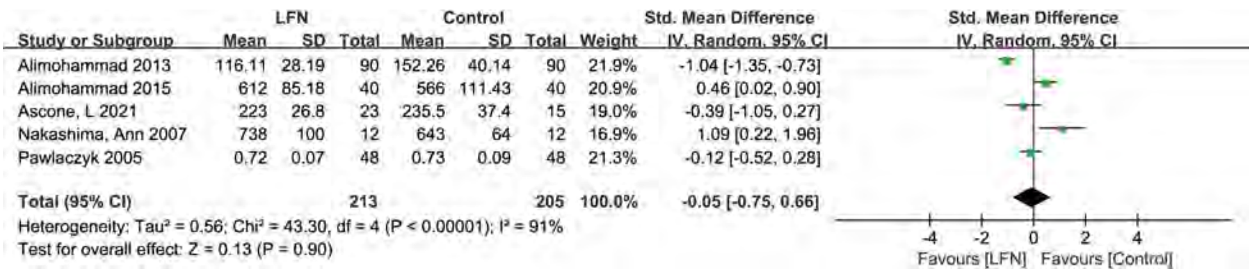

Fig. 3 Forest plot of the effect of LFN on Attentional functioning domain

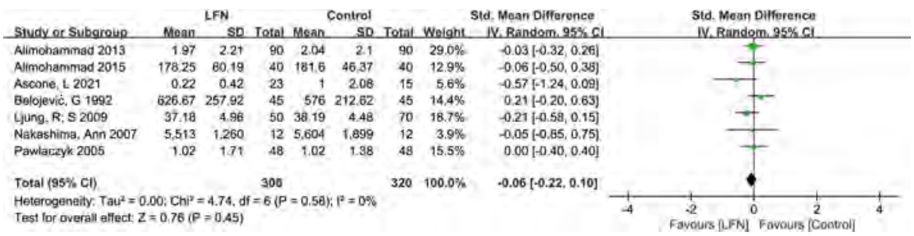

Fig. 4 Forest plot of the effect of LFN on Executive functioning domain

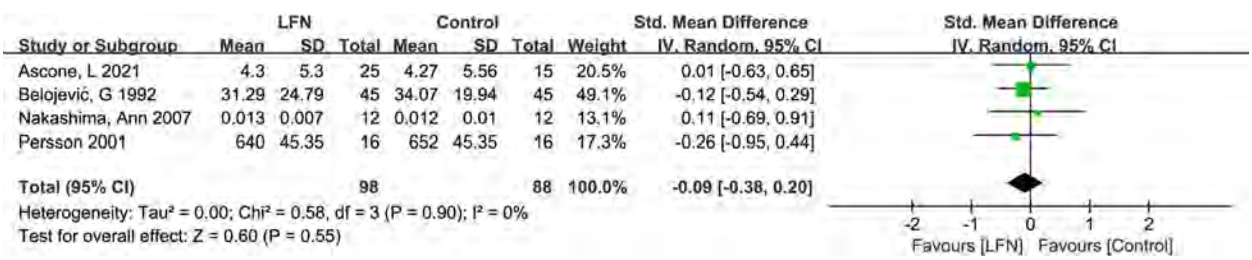

Fig. 5 Forest plot of the effect of LFN on Memory domain

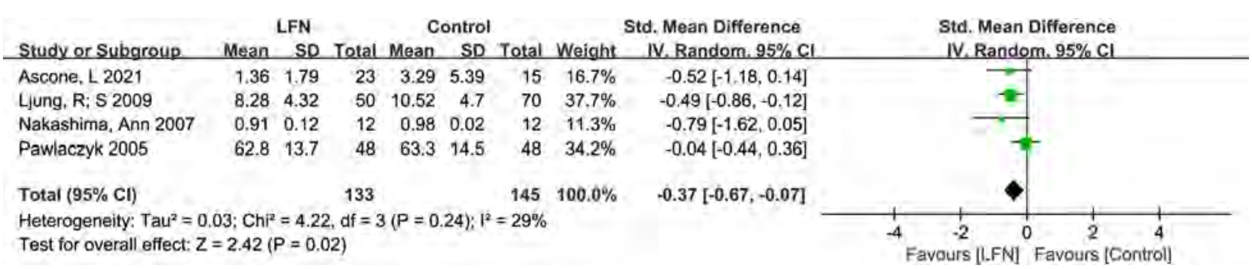

Fig. 6 Forest plot of the effect of LFN on Higher-order functions domain

no heterogeneity between the results of relevant studies in the domains of executive function and memory, but heterogeneity was higher within the attention domain, which aligns with the findings of Thompson et al. [52], who demonstrated that noise exposure worsens cognitive impairment and reading ability but has no effect on executive function. This may be because basic cognitive functions are more readily achieved and that the influence of LFN is not substantial enough to affect these simpler cognitive functions. Alternatively, the impact of LFN on basic cognitive functions could be too small for our selected detection indicators to determine [39]. We noted that the impact of LFN on cognitive functions may also be related to each individual's noise sensitivity, which could potentially be the primary reason for changes in cognitive function [6, 26, 53].

Limitations

In this study, we summarized literature concerning the relationship between LFN and cognition in the general (non-pathological) population up until December 2022. Two authors independently used rigorous scientific methods to assess the risk of bias. We categorized cognitive function into four domains and analyzed each, specifically focusing on LFN, an issue of increasing public health interest. Our findings revealed that, while LFN interventions may not substantially impact basic cognitive function, they could potentially negatively affect higher-order cognitive functions. These results are useful in the development of protective measures against LFN.

This study has some limitations. First, because research solely addressing LFN is relatively scarce and the cognitive tasks among studies are different, standardizing the exposure dose of LFN, including frequency, sound pressure level, exposure method, and intervention time, when incorporating the literature is challenging. This could have potentially affected the quality of evidence concerning the relationship between LFN and cognitive function. Second, cognitive function is broad, and representing changes in cognitive function from a single perspective may be somewhat one-sided. Even though we categorized and analyzed cognitive function, the summarization process may still be subjective. Finally, because of limitations in LFN research, the number of studies and population covered in our study were limited. Meanwhile, considering the GRADE assessment of current evidence is of poor quality, the conclusions demonstrated herein cannot be generalized.

Future research directions

The impact of LFN on basic cognitive functions may be too small to detect or may depend on individual noise sensitivity. Studies delving into the impact of LFN on cognitive function are lacking, with the scope of populations involved in these studies being relatively narrow. First, to conduct research of higher quality on the relationship between LFN interventions and cognitive functions, it is of paramount importance to conduct multi-center studies that comprise the entire population and include larger sample sizes.

Second, a unified standard for the methods and intensity of LFN interventions is yet to be established, and the selection of methods to evaluate cognitive function also varies. Although our study carefully selected situations involving LFN interventions and classified domains of cognitive function, the presence of confounding factors still poses a limitation on comparability across studies.

Third, given the potential role of noise sensitivity in its impact on cognitive function, future research demands a more profound exploration of this contributing factor. Furthermore, it should be incorporated into the inclusion criteria for study participants in a standardized manner.

Finally, it is hoped that the protection standards for LFN can be improved, and the subjective protection awareness of long-term exposure groups to actively protect against LFN can be improved, such as wearing noise reducing earphones and controlling the duration of noise exposure.

Conclusions

Through this meta-analysis, we aimed to explore the influence of LFN intervention on cognitive function. Our research indicated that, to date, there is no evidence supporting the notion that LFN intervention impacts attention levels, executive function, and memory. However, there is evidence of low quality showing that LFN intervention may lead to a reduction in higher-order cognitive functions, including reasoning and mathematical calculation. This impact may be associated with the level of cognitive load and susceptibility to noise. When the future research is conducted, these two factors and their interventions must be considered. In practical scenarios, attention should be directed toward the negative consequences of LFN during noise protection, and relevant protective measures should be implemented.

Abbreviations

LFN	Low-frequency noise
SMD	Standardized mean difference
CI	Confidence interval
PECOS	Participants, exposure, control/comparison, outcomes, and study design
RoB 2	Revised Cochrane risk of bias tool for randomized trials
GRADE	Grading of Recommendations Assessment, Development, and Evaluation

Supplementary Information

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Additional file 1. The PRISMA 2020 checklist of this review.

Additional file 2. The Literature Search Strategy of this review.

Additional file 3. Detailed information for effect sizes transformation.

Additional file 4. Exclusion reasons for 42 full-text articles.

Additional file 5. The individual study bias analyses of this review.

Additional file 6. GRADE summary for quality of evidence from LFN associated with cognitive function.

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Authors' contributions

PL originated the research idea, carried out the study and prepared the manuscript. Study design: PL, JW. Literature research and screen: PL, JJL. Data extraction: ZLL, JW. Critical appraisal: JW, JL. Critical appraisal: SHZ, SLX.

Statistical analysis: PL, ZHL. Manuscript writing: PL, ZHL, JW.All authors have read and approved the final manuscript. Zhaohui Liu and Jin Wang are the co-corresponding authors of this article.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

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Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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The Impact of Noise on Learning in Children and Adolescents: A Meta-Analysis

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Abstract: Given the growing body of research on the impact of noise, synthesizing these findings is crucial to gaining a comprehensive understanding of the influence of noise on student performance. This meta-analysis investigates the effects of environmental and classroom noise on learning, with a focus on cognitive and academic performance in elementary and secondary school students. A systematic review and meta-analysis were conducted on 21 studies comprising 152 effect sizes. Different noise types were analyzed in relation to cognitive functions such as attention, memory, comprehension, and overall academic performance. The Restricted Maximum Likelihood (REML) method was used to estimate the overall effect size, resulting in a value of −0.46 (95% CI: −0.54 to −0.38), indicating the moderate negative impact of noise on performance. The negative effects were particularly significant in children aged 6 to 12. Despite high heterogeneity across the studies, likely due to variations in noise types and study designs, model fit measures confirmed the adequacy of the meta-analytic model. These findings underscore the importance of mitigating noise in educational settings to improve students' cognitive and academic outcomes.

Keywords: noise impact; student performance; meta-analysis; cognitive functions; educational environment

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1. Introduction

Noise, defined as any unwanted sound, has been a growing concern in modern society [1]. It is regarded as the third most pressing environmental concern after water and air pollution [2]. In this context, it is important to consider the impact of noise on learning and cognitive performance in children and adolescents, as this population is particularly vulnerable to its effects [3].

The impact of noise on academic and cognitive performance has been a significant area of research. Several systematic reviews and meta-analyses have addressed different aspects of this issue, providing a still-varied understanding of how noise affects different population groups and types of cognitive skills as well as health and well-being. Below is a brief description of key studies that have explored this relationship, highlighting their main findings and how they differ from the present meta-analysis.

One study [4] conducted a comprehensive meta-analytic synthesis on the effects of noise on human performance, highlighting noise as a significant stressor affecting cognitive and motor responses. This study, which included only adult participants, revealed that the type of noise and the nature of the task were key moderators. Investigating the effects of aircraft noise on children's reading comprehension and psychological health, Ref. [5] analyzed data from three studies conducted in 106 schools near major airports. They found aircraft noise was associated with a decrease in reading comprehension and an increase in hyperactivity, with no effects on emotional symptoms or conduct problems. The authors of [6] evaluated the effects of everyday environmental noise on non-pathological cognitive abilities in individuals, presenting an updated systematic review of noise pollution and human cognition. Their study covered the entire lifespan and used epidemiological studies to inform policies on noise pollution. In a systematic review and meta-analysis, Ref. [7] found that low-frequency noise had a significant negative impact but only on higher-order cognitive functions.

More recently, Fernández–Quezada et al. conducted a meta-analysis on the effects of noise on cognitive performance in young populations, providing additional insights into how different noise sources influence cognitive functions. While this study contributes to the growing body of research on noise-related impacts, the present meta-analysis focuses specifically on academic and cognitive performance in school settings, employing strict inclusion criteria that prioritize experimental and quasi-experimental studies with objective measurements [8].

Our meta-analysis differs from previous studies by assessing how both environmental and classroom noise affect the cognitive and academic performance of children and adolescents. The use of meta-analytic techniques allows us to synthesize findings from multiple independent studies, providing a more comprehensive and statistically robust estimate of the overall effect of noise. This is particularly important given the variability in study designs, noise exposure conditions, and outcome measures found in individual research efforts.

By integrating data from diverse studies, a meta-analysis increases their statistical power, enhances the generalizability of findings, and helps identify potential moderating factors, such as types of noise and student characteristics like age. This systematic approach not only strengthens the validity of the studies' conclusions but also provides valuable synthesized information that can guide educational policies and future research on mitigating the impact of noise in learning environments.

The aim of this study is to analyze the impact of noise on learning in a learning environment through assessing the academic and/or cognitive performance of non-university students. To achieve this objective, this study will address the following research questions:

(a) What is the overall effect of noise on learning in terms of the academic or cognitive performance of students?
(b) How do characteristics such as noise intensity, noise type, and the age of students influence this effect?

2. Materials and Methods

2.1. Research Protocol

A systematic review of the literature and meta-analyses was conducted following the stages of identification, screening, eligibility, and inclusion outlined in the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses, 2020) [9].

For the search procedure, Scopus and Web of Science databases were used. The keywords for the search in this study were as follows: (acoustics OR noise) AND (academic AND performance OR cognitive AND performance OR learning) AND (classroom OR school). Restrictions were applied such that the search fields included were "Title, Abstract, and Keywords".

To address publication bias, we contacted experts in the field. Specifically, we reached out to an author through the ResearchGate network to request unpublished studies but the author sent a study that turned out to have been published.

2.2. Inclusion and Exclusion Criteria

The search for articles and sources was conducted exhaustively and systematically. Studies that met the following criteria were included: (a) the influence of noise on the cognitive and/or academic performance of students is examined in a school context; (b) the effects of noise analyzed include cognitive processes such as memory, attention, problem-solving, or reading comprehension and are measured through validated instruments or scales, not based on participants' perceptions; (c) academic performance grades are also included; (d) participants are non-university students from regular schools who do not have apparent hearing or learning difficulties; (e) the study design is experimental or quasi-experimental; (f) sufficient data are provided to calculate the effect size; (g) the study is written in English, Catalan, Spanish, or Portuguese; (h) the study is on the effect of noise on behavior, comfort, or speech perception and comprehension.

2.3. Codification of Studies

A protocol was developed to record the characteristics of the studies and determine which factors might influence the results. For this purpose, methodological characteristics, the characteristics of the study object, participant characteristics, and extrinsic characteristics were separated. Below are the indicators for each set of characteristics:

(a) Methodological characteristics: type of design, cross-sectional or longitudinal study, instrument for measuring cognitive processes, or measure of academic performance.
(b) Characteristics of the study object: cognitive process evaluated (attention, memory, comprehension, reading, etc.), academic subject or type of noise detected.
(c) Participant characteristics: age, academic grade, sample size, country.
(d) Extrinsic characteristics: year of publication, source.

2.4. Analysis of Information

For each selected study, we calculated Cohen's d effect size using the provided means and standard deviations (SDs). In some cases, we also used the partial eta squared ($\eta^2 p$) to calculate Cohen's d. Additionally, we calculated the standard error (SE) of each effect size using a formula based on sample sizes. These calculations are necessary to integrate and compare the results of multiple studies in a meta-analysis.

In the process of synthesizing and interpreting the effect sizes of various studies, it was necessary to adjust the signs of some effect sizes to ensure consistency in the interpretation. Specifically, in our meta-analysis, a positive effect size consistently indicates better performance or a less negative impact under the experimental condition, whereas a negative effect size indicates worse performance or a more significant negative impact under the experimental condition. For example, if a study reported a positive effect size for an experimental condition that led to poorer performance compared to the control condition, we reversed the sign to maintain uniformity.

3. Results

3.1. Qualitative Synthesis

A summary of the studies and their characteristics and findings is provided in Table S1 (the effect sizes, sample sizes, and age ranges covered, etc.), which serves as a reference for the analyses that follow.

This meta-analysis included a diverse range of studies examining the influence of noise on students. Most of the studies focused on elementary school students, like those in [10,11], which examined students aged 7–11 and 10–12, respectively. Secondary school students were also well represented, as seen in studies [12,13], which focused on children aged 11–16 and 14–18. This broad age range and the different stages of learning provide a comprehensive view of how noise impacts children differently.

There is considerable variability in the sample sizes of the studies. The smallest samples consist of 17 participants [14] and 20 participants [15]. Intermediate sample sizes were common, as seen in [10,16], which featured samples ranging from 142 to 186 participants. Large-scale studies such as those in [12,17] included extensive sample sizes of 976 and 989 participants, respectively. Additionally, some studies report data based on the number of schools rather than individual participants, indicating potentially large sample sizes, such as 142 primary schools in central London [10] and 96 secondary schools in Greater London [18].

The studies were conducted in various countries, including Australia, Italy, the United Kingdom, Korea, the United States, Brazil, China, Germany, and Sweden. However, this reveals that certain regions, such as Africa, South America (excluding Brazil), and large parts of Asia, are underrepresented in this body of research.

In the analysis of the studies included, various effects of noise on different cognitive and academic performance were identified.

3.1.1. Impact of Classroom Noise

The impact of classroom noise on students' cognitive and academic performance is significant and multifaceted. Studies indicate that classroom noise affects various cognitive functions and academic outcomes. For instance, ref. [19] found that classroom noise significantly impacts students' reading fluency. Similarly, ref. [20] observed that noise affects sentence comprehension, with variations depending on children's selective attention. Children with low selective attention exhibited a significant increase in response time under noisy conditions.

The authors of [15] investigated the effects of classroom noise on writing, arithmetic, and reading skills. Their findings showed moderate effects favoring the experimental group exposed to noise in most assessments. In addition, ref. [14] found that noise had a significant impact on nonword repetition accuracy and verbal processing time. They observed reduced accuracy and increased processing times under noisy conditions.

In their report, the authors of [16] highlighted improvements in listening comprehension, nonverbal processing, and spelling with classroom sound field systems, implying that well-managed classroom acoustics can mitigate some of the negative effects of noise. Similarly, [17] found high aircraft noise exposure resulted in small yet noteworthy variations in reasoning, vocabulary, and perception scores when compared to low-noise-exposure groups.

The study [21] focused on speech perception and listening comprehension, finding significant differences under varying classroom noise conditions. In [22], it was demonstrated that adequate acoustic conditions improve verbal working memory and reduce errors such as omissions and intrusions.

The study [19] revealed a noteworthy influence of classroom noise on students' reading fluency, with an effect size of 0.34. In [20], it was noted that sentence comprehension, both in terms of accuracy and response time, was variably impacted depending on children's selective attention. Children with high selective attention showed no significant differences in accuracy under different noise conditions, while those with low selective attention exhibited a significant increase in response time under noisy conditions.

3.1.2. Impact of Environmental Noise

Previous findings highlight the complex relationship between environmental noise and cognitive and academic performance. In [23], it was highlighted that environmental noise negatively influences cognitive flexibility and general executive control, with the effect sizes of noisy environments ranging from 0.54 to 0.62. The study [24] examined calculation performance and found that performance is marginally better in silent conditions and worse in the presence of traffic and classroom noise. Similarly, Ref. [12] reported that the effect of noise level on students' reading comprehension had an effect size of 0.29 and that there was an interaction between noise and age.

In terms of studies on overall academic performance, ref. [13] identified a moderate negative correlation between urban school noise and GPA and MAP scores, indicating that higher noise levels are associated with poorer academic performance. Additionally, ref. [11] investigated various cognitive and academic domains, including arithmetic, vocabulary, and block design, observing effect sizes ranging from 0.12 to 0.47. Regarding visual selective attention errors, ref. [11] also found that background noise affects divided and selective attention, although not all differences were statistically significant.

A study on the impact of classroom noise found moderate effects on writing, arithmetic, and reading skills favoring the experimental group in most assessments [15]. Previous research has examined nonword repetition accuracy and verbal processing time, observing significant reductions in accuracy, with reduced bandwidth and differences in processing time, under various SNR conditions [14].

Small to moderate improvements in listening comprehension, nonverbal processing, and spelling were reported in a study on classroom sound field systems [16]. The relationship between noise and academic performance was examined in a study that found weak positive and negative correlations depending on the specific variables analyzed [18]. Significant negative effects on reading and mathematics were observed, particularly among students with socioeconomic disadvantages and those with English as an additional language [10].

Small but significant differences in reasoning, vocabulary, and perception scores were found between high- and low-aircraft-noise-exposure groups [17]. Speech perception and listening comprehension were investigated, with significant differences observed under different classroom noise conditions [21]. The impact of noise on verbal memory was explored, demonstrating that adequate acoustic conditions improve working memory and reduce omissions and intrusions [22].

Ref. [25] found a negative relationship between higher environmental noise levels (LAeqN) and math and reading scores, but it also identified positive links with a better signal-to-noise ratio (SNR). It was found that a better SNR significantly improves children's auditory comprehension [26]. Another study highlighted the importance of a good SNR for sentence recognition, with significantly better performance observed under favorable acoustic conditions [27]. The effects of traffic noise and irrelevant speech on reading comprehension and speed, as well as basic mathematics and mathematical reasoning skills, were investigated, showing that traffic noise moderately impairs reading comprehension and speed, while irrelevant speech has minimal effects [28]. Chronic aircraft noise exposure was found to have a small negative effect on students' reading comprehension and sustained attention [29]. Noise level and type were observed to have small effects on attention, short-term memory, and performance in calculation and reading tasks [30].

3.1.3. Cognitive and Academic Processes

This meta-analysis examined a variety of processes that affected learning when students were exposed to noise. These processes were classified into larger categories:

1. Language comprehension and processing—reading fluency, listening comprehension, writing skills, and spoken word perception.

2. Processing speed—response times during reading, verbal processing, and selective attention tasks.
3. Executive control—cognitive flexibility, problem-solving, and interference management (e.g., the Stroop test).
4. Attention—selective and sustained attention in visual and auditory tasks.
5. Mathematical skills—arithmetic, problem-solving, and mathematical reasoning.
6. Academic performance—overall achievement as tested through standardized tests (e.g., NAEP) and GPAs.
7. Visuospatial skills—pattern recognition and spatial organization.
8. Memory—working memory, verbal and visual recall, and spatial memory.

3.2. Quantitative Synthesis

The Restricted Maximum Likelihood (REML) method was used to estimate random effects. REML is a robust and suitable technique for meta-analyses when variability is expected between studies, as it adjusts the estimation of the variance of random effects, providing a more precise estimate compared to less sophisticated methods. This method is particularly useful when sample sizes vary between studies and an unbiased estimation of heterogeneity is desired. However, REML assumes that effect sizes follow a normal distribution, which may not always hold in cases of strong skewness or extreme heterogeneity. Additionally, its accuracy depends on the correct specification of its moderators.

The Omnibus Test of Model Coefficients was performed to evaluate the overall significance of the model. The test yielded a Q value of 36.921 with 17 degrees of freedom, and the result was statistically significant ($p < 0.001$). This indicates that the model coefficients all collectively contribute to the prediction of the outcome variable, as shown in Table 1.

Table 1. Fixed and random effects.

	Q	**df**	***p***
Omnibus Test of Model Coefficients	36.921	17	<0.001

Note. Q = Omnibus test statistic; df = degrees of freedom; p = p-value. The model was estimated using Restricted ML method.

The fit measures for the REML estimation method indicate the adequacy of the model in explaining the data's variability (Table 2). The Log-Likelihood value was –95.417, the Deviance was 190.834, the Akaike Information Criterion (AIC) was 228.834, the Bayesian Information Criterion (BIC) was 283.893, and the Corrected Akaike Information Criterion (AICc) was 235.500. These measures suggest that the model provides a reasonable fit for the data, with lower AIC, BIC, and AICc values indicating good model performance.

Table 2. Fit measures.

	REML
Log-Likelihood	−95.417
Deviance	190.834
AIC	228.834
BIC	283.893
AICc	235.500

In the analysis of the coefficients (see Table 3, and note that it is split across two pages due to space limitations), the intercept was statistically significant, with an estimate of −0.352 (p = 0.020), indicating a negative baseline effect when all other variables are held constant. This suggests that even in the absence of specific moderating factors such as noise type or student age, noise exposure has a detrimental impact.

Table 3. Coefficients.

	Estimate	S.E	Z	p
Intercept	−0.352	0.152	−2.319	0.020
Noise (Environmental noise)	0.136	0.177	0.765	0.444
Noise (Classroom noise)	−0.161	0.206	−0.780	0.436
Noise (High environmental noise)	−0.045	0.197	−0.227	0.820
Noise (Traffic noise)	0.477	0.280	1.704	0.088
Age_sta (Children)	−0.350	0.129	−2.714	0.007
Age_sta (Younger)	0.029	0.167	0.173	0.863
Age_sta (Other)	0.291	0.373	0.781	0.435
Age_sta (Older)	−0.041	0.208	−0.198	0.843
Age_sta (Teen)	−0.015	0.493	−0.031	0.975
Level (Secondary)	0.094	0.171	0.549	0.583
Function (Executive control)	−0.062	0.203	−0.307	0.759
Function (Processing speed)	0.011	0.190	0.058	0.954
Function (Memory)	−0.127	0.172	−0.738	0.461
Function (Mathematical skills)	0.217	0.120	1.805	0.071
Function (Attention)	−0.032	0.192	−0.168	0.866
Function (Language comprehension and processing)	−0.152	0.153	−0.998	0.318
Function (Visuospatial skills)	−0.064	0.352	−0.181	0.856

Note. Wald test. Estimate = estimated effect size; S = standard error; E = expected value; Z = Z-score; p = p-value.

The age category "Children" (6–12 years) showed a highly significant negative effect (−0.350, p = 0.007), reinforcing previous findings that younger students are more vulnerable to noise-related disruptions. This may be attributed to the developing of executive functions in this age group, making it harder for them to filter out auditory distractions.

Regarding noise type, traffic noise exhibited a positive effect (0.477, p = 0.088), which is unexpected given the typically negative effects of environmental noise on learning. Although this result does not reach statistical significance, it may reflect complex compensatory mechanisms, where students exposed to traffic noise over time develop adaptive cognitive strategies. Alternatively, it could indicate that certain studies included in the meta-analysis measured background traffic noise differently, leading to variability in the reported effects. Further research is needed to explore whether low-level traffic noise could serve as a masking noise, reducing the impact of disruptive intermittent sounds, as observed in some studies on white noise.

On the other hand, classroom noise exhibited a negative effect (−0.161, p = 0.436), consistent with expectations that higher noise levels within the learning environment can impair student concentration and performance. However, the high p-value indicates substantial variability across studies, suggesting that not all types of classroom noise have the same effect. Factors such as the source of noise (e.g., teacher vs. students talking, external disturbances), classroom design (acoustics, size), and task complexity could be influencing the degree of impairment observed.

Similarly, memory (−0.127, p = 0.461) and language processing (−0.152, p = 0.318) showed negative trends, though they did not reach statistical significance. The lack of significance may stem from differences in study designs, noise exposure conditions, or measurement tools used across studies.

Finally, high environmental noise (−0.045, p = 0.820) and visuospatial skills (−0.064, p = 0.856) were not significantly impacted, which suggests that not all cognitive functions are equally affected by noise exposure. It is possible that tasks relying on visual processing and spatial reasoning are less dependent on auditory conditions, making them more resistant to external distractions.

The analysis of the residual heterogeneity estimates presented in Table 4 revealed significant residual heterogeneity among the studies, as indicated by a τ^2 value of 0.207 and an I^2 value of 96.943%. This high I^2 value suggests that approximately 97% of the variability in effect sizes is due to differences between the studies rather than sampling errors. The test of residual heterogeneity (Q) further supports this, with a value of 8320.079 (df = 134, $p < 0.001$), indicating that the heterogeneity is statistically significant. These results highlight the variation in the effects of noise on cognitive and academic performance across these studies. The heterogeneity could be attributed to several factors, including the large number of reported effect sizes; differences in participant ages, academic levels, and types of noise; and the variety of cognitive and academic processes assessed.

Table 4. Residual heterogeneity estimates.

Parameter	Estimate
τ^2	0.207
T	0.455
I^2 (%)	96.943
H^2	32.715

3.3. Visualization of Meta-Analysis Results

The following section presents the graphical tools used to visualize the results of the meta-analysis, specifically, the funnel plot (Figure 1). A forest plot is included in the Supplementary Materials (Figure S1). The effect size of −0.46 indicates an effect of a moderate magnitude according to Cohen's guidelines. This suggests that the independent variable (in this case, noise) has a negative impact on the dependent variable (academic or cognitive performance). In other words, as noise increases, academic or cognitive performance decreases. The 95% confidence interval (−0.54 to −0.38) indicates that since the interval is below zero and does not include zero, we can affirm that the negative effect of noise is significant and not due to chance.

Most effect sizes are located on the left side of the line, indicating a negative impact of noise on performance. The most substantial negative values correspond to −3.01 [−3.07, −2.95], reported by [17], with a small confidence interval; −2.98 [−3.50, −2.46] and −2.40 [−2.92, −1.88], reported [14]; −2.63 [−3.06, −2.20], reported by [21]; and −2.0 [−2.56, −1.44], reported by [27].

The study [17] reported a large effect size, demonstrating that there was a significant difference in perception scores between the high exposure and control groups in a large sample of 989 participants. Similarly, ref. [14] highlighted a significant reduction in accuracy with reduced bandwidth, noting higher accuracy at a 9 dB SNR compared to a 3 dB SNR in nonword repetition accuracy, although its sample size was limited to 17 subjects. In another study, ref. [21] discovered that noise negatively affects speech perception in children aged 6–8 years. Their comparison of silence to binaural conditions (LAeq = 63 dB, SNR-3dB) revealed a significant negative effect, underscoring the detrimental impact of noise on young children's ability to understand speech. Moreover, ref. [27] demonstrated a significant negative impact of classroom noise and reverberation on comprehension performance in elementary-aged students. The study used a simulated classroom environment with varied reverberation times and background noise levels, showing that both reduced performance in comprehension tasks.

detrimental impact of noise on young children's ability to understand speech. Moreover, ref. [27] demonstrated a significant negative impact of classroom noise and reverberation on comprehension performance in elementary-aged students. The study used a simulated classroom environment with varied reverberation times and background noise levels, showing that both reduced performance in comprehension tasks.

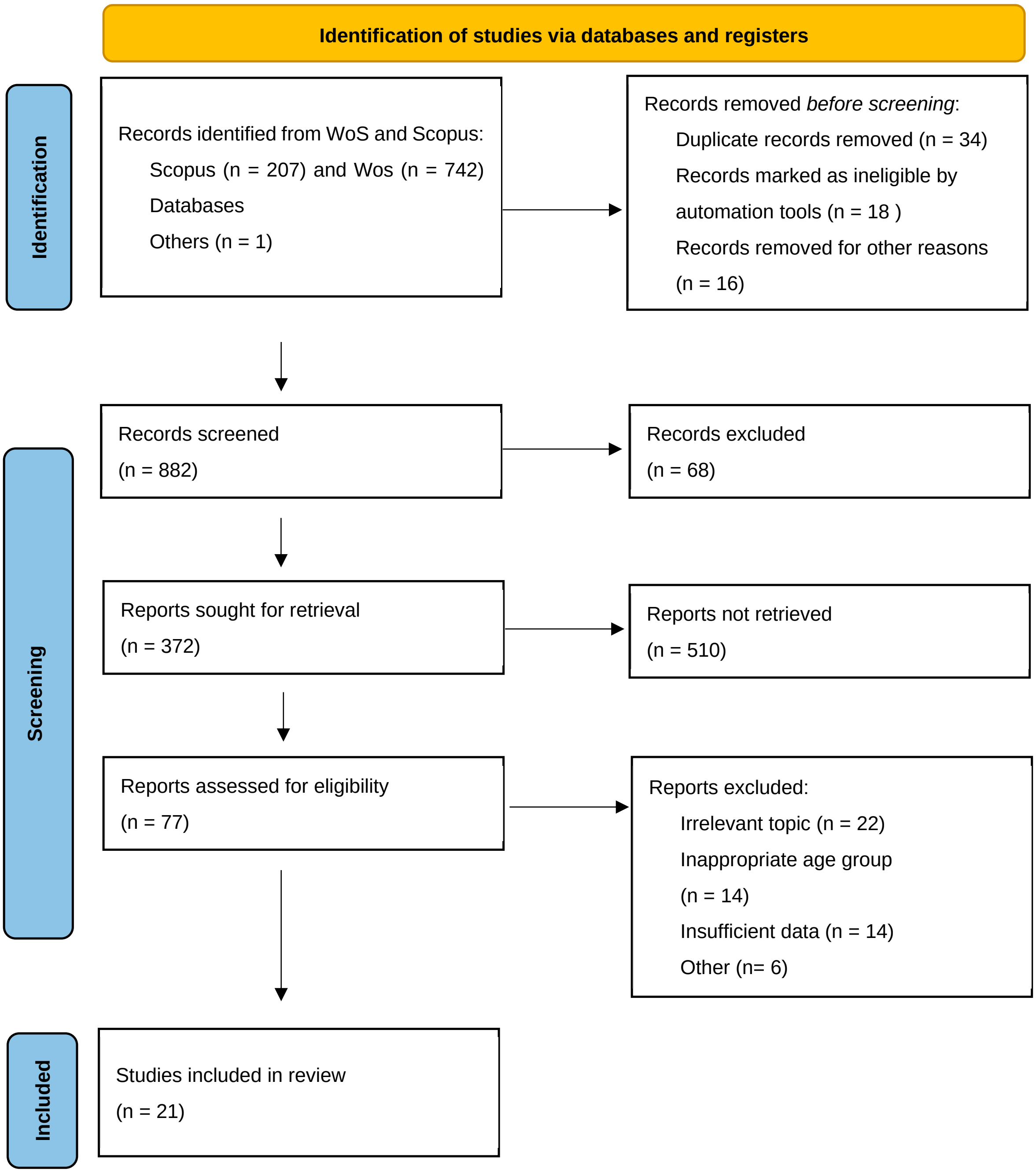

Figure 1. PRISMA flow diagram.

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In contrast, the positive effects reported were small and not significant, as they included 0. Ref. [28] reported a small effect of irrelevant speech on reading comprehension, with LAeq = 66 dBA and background babble around 62 dBA and with the dominant frequency range between 500 and 1500 Hz, indicating that irrelevant speech slightly improves reading comprehension, although the effect size was small. Ref. [15] compared classroom noise in a control versus experimental group in the first evaluation of 8-year-old participants it conducted. The results showed a slight favoring of the control group, but this difference was not significant, and the authors could not explain this outcome.

In contrast, the positive effects reported were small and not significant, as they included 0. Ref. [28] reported a small effect of irrelevant speech on reading

The funnel plot (Figure 2) showed a reasonably symmetrical distribution of points around the mean effect value, suggesting a partial absence of publication bias. Most studies clustered around the center, indicating that the estimated effect sizes are generally

consistent and reliable. However, some asymmetry was observed in the lower part of the plot, which may indicate the presence of small-study effects or potential publication bias.

To further assess this, Egger's regression test for funnel plot asymmetry was conducted, revealing significant asymmetry (Z = −4.764, $p < 0.001$), suggesting the presence of publication bias. This result indicates that studies proving the significant negative effects of noise on learning may be overrepresented, while studies reporting neutral or positive effects might be underreported in the literature. Given this, the overall effect size of noise on learning could be slightly overestimated.

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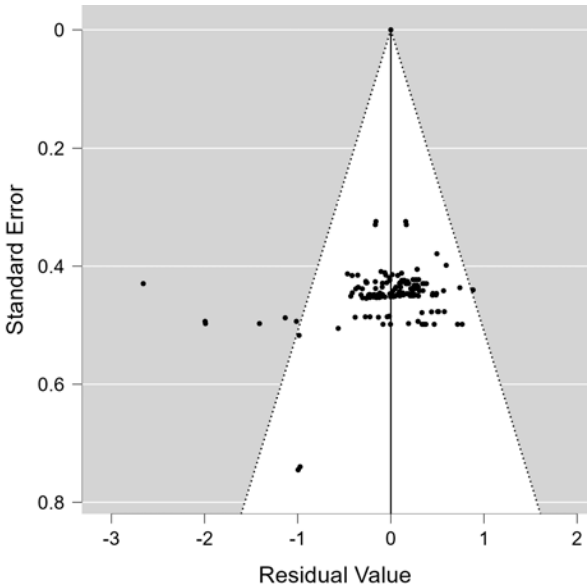

Figure 2. Funnel plot.

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4. Discussion and Conclusions

The aim of this meta-analysis was to analyze the impact of noise on learning through the academic and/or cognitive performance of non-university students, specifically children and adolescents. To achieve this goal, the following research questions were addressed:

(a) What is the overall effect of noise on the academic or cognitive performance of students? The results, based on 21 studies and 152 effect sizes, show that noise has a significant negative impact on academic and cognitive performance, with a moderate effect size of −0.46 according to Cohen's guidelines. This finding suggests that as noise levels increase, performance decreases. The statistical significance of this effect, supported by a 95% confidence interval that does not include zero, highlights the importance of considering noise as a critical factor in educational settings.

(b) How do characteristics such as noise intensity, noise type, and the age of students influence this effect? The coefficient analysis revealed that the "Children" age category (between 6 and 12 years old) led to highly significant results, with an estimate of −0.350 ($p = 0.007$), indicating that younger students perform significantly worse under noisy conditions. This finding emphasizes the need for effective policies and strategies to mitigate noise in classrooms, especially for younger students, who are particularly vulnerable.

Although classroom noise was not statistically significant, it showed a negative trend, with an estimate of −0.161 ($p = 0.436$), indicating a possible negative relationship between this type of noise and academic performance. Similarly, memory and language functions also showed negative trends, with estimates of −0.127 ($p = 0.461$) and −0.152 ($p = 0.318$), respectively.

It is also worth noting that traffic noise showed a positive estimate of 0.477 (p = 0.088), but this result was not statistically significant. This inconsistency may be due to complex interactions with other variables that were not adequately controlled in the included studies.

This study has several limitations. First, despite including multiple studies in this meta-analysis, the high degree of heterogeneity among the studies may have influenced the results. Second, variability in the measurement of noise and academic/cognitive performance across studies may have introduced biases. Differences in noise measurement methods (e.g., objective decibel levels vs. self-reported exposure) and variations in the cognitive and academic processes assessed (e.g., reading comprehension, memory, mathematical reasoning) contribute to this heterogeneity. Similarly, differences in participant characteristics (e.g., age, educational level) may influence the extent to which noise affects learning.

While this meta-analysis provides a general estimate of the effect of noise on learning, the heterogeneity within it suggests that noise does not impact all students and cognitive functions in the same way.

Third, there is evidence of publication bias, as studies reporting significant results are more likely to be published. This may have led to a slight overestimation of the overall effect size.

Fourth, the use of the REML method, while appropriate for estimating random effects, assumes that effect sizes follow a normal distribution and may be sensitive to extreme heterogeneity or moderators. Although the REML method provides a robust variance estimation, these assumptions should be considered when interpreting the results.

Additionally, there were challenges in categorizing age groups, as the age ranges defined in the studies sometimes overlapped, although they were organized in the most useful way possible for analysis.

Lastly, although a meta-analysis aims to generalize results for a broader population, the diversity of the educational contexts and populations studied may limit the universal applicability of these findings.

In conclusion, our findings emphasize the importance of minimizing acoustic distractions to create optimal learning environments for students. This meta-analysis provides strong evidence of the negative impact of noise on academic and cognitive performance, particularly among younger students, who appear more vulnerable to its effects.

However, the variability across studies suggests that the impact of noise is not uniform across all educational settings, as it may depend on factors such as noise type, intensity, and student characteristics. This highlights the need for future research to refine noise exposure assessments, investigate potential moderating variables, and expand the range of studies included to improve the generalizability of these findings.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app15084128/s1, Figure S1: Forest plot, Table S1: Summary of studies.

Author Contributions: Methodology, G.F. and R.P.; Software, G.F.; Validation, G.F. and R.P.; Formal analysis, G.F.; Investigation, G.F.; Data curation, G.F.; Writing—original draft, G.F.; Writing—review & editing, G.F. and R.P.; Visualization, R.P.; Supervision, R.P.; Project administration, R.P. All authors have read and agreed to the published version of the manuscript.

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April 15, 2026

Gaines Township Planning Commission
8555 Kalamazoo Avenue SE
Caledonia, MI 49316

RE: Microsoft's Rezoning Requests for Five Parcels for a Data Center

Dear Gaines Township Planning Commission:

As a resident of Gaines Township, I strongly oppose the rezoning request by Microsoft for the five parcels located at 7147 Patterson Avenue SE, 4233 76th Street SE, 4367 76th Street SE, 4645 76th Street SE, and 6930 East Paris Avenue SE all in Caledonia, Michigan 49316 (hereinafter the "Parcels"). As detailed below, Microsoft's rezoning request does not meet the requirements of the Zoning Amendment Approval Standards in § 31.40 A of the Township's Zoning Ordinance. Additionally, if the Planning Commission approves this request, it will cause irreparable harm to the community and environment.

I will address portions of the Zoning Amendment Approval Standards under § 31.40 A of the Township's Zoning Ordinance in turn below.

2. The rezoning of the land will not negatively impact adjacent and nearby property:

a. **The allowable land uses within the proposed zoning district are compatible with nearby land uses and zoning districts.**

The Report submitted by Dan Wells, Community Development Director (hereinafter the "Report"), states that the rezoning request meets the standard for this requirement. However, the Report fails to state in this section the 24 adjacent properties to the Parcels that would be negatively impacted by this rezoning request. The two properties are located to the east of the Parcels along Patterson Avenue (7081 Patterson Avenue SE and 7147 Patterson Ave SE) are both zoned as Agricultural/Rural Residential. Additionally, there are approximately 18 homes on parcels in the Carpet Rose neighborhood located to the southwest of the Parcels that are all zoned as Planned Unit Development and two more homes on parcels on 76th Street SE zoned as Agricultural/Rural Residential (3959 76th Avenue SE and 3957 76th Avenue SE). All 24 homes located adjacent to the Parcels would be negatively impacted by the rezoning of the Parcels.

Pursuant to the Township's Zoning Ordinance § 12.10 A, a light industrial zone "should have . . . significant separation and buffering from residential areas." A buffer, at a minimum, is "[a] strip of land which provides visual separation and aesthetic relief between potentially incompatible uses or provides protection to natural resources through the use of landscaping, preservation of existing vegetation, berms, or screening, or a combination of materials." Zoning Ordinance § 35.10. Significant separation is not defined under the Zoning Ordinance, but it can be assumed to mean a greater distance than abutment.

Microsoft's latest Addendum to its Rezoning Application (hereinafter the "Application") notes that "a set of residential lots [are located] to the east" of the Parcels. Furthermore, their Application tries to dismiss that this issue by saying that "[t]he majority of those are in Caledonia Township and separated from the [Parcels] by Patterson Avenue." Microsoft simply does not address the remaining 22 other homes that are adjacent to the Parcels that are located within Gaines Township.

The Zoning Ordinance is clear that a light industrial parcel requires "significant separation and buffering from residential areas." § 12.10 A. Unlike Microsoft implies, there is no distinction in the law between a few residential properties or many. Residential properties that share a property line with a light industrial property would directly violate the zoning law as they would not be "significantly separated." § 12.10 A. Furthermore, Patterson Avenue does not qualify as a buffer between a light industrial zone and a residential zone. By definition, a buffer is a "strip of land" and separates areas through "landscaping, berms, preservation of existing vegetation, or screening." Zoning Ordinance § 35.10. An asphalt road, Patterson Avenue specifically, does not fall under the definition of a buffer as it is not vegetation, landscaping, a mound of dirt, etc.

Overall, the Report and Application fail to address the residential properties that are adjacent to the Parcel. When those residential properties are considered, rezoning the Parcel would be in violation of the Zoning Ordinance's requirements for significant separation and buffers between light industrial areas and residential areas.

b. There will be no adverse physical impact on surrounding properties.

Unlike the Report and Application state, there will be adverse physical impacts on surrounding properties. Microsoft and the Mr. Wells are again ignoring the residential properties that abut the Parcels and the community at large.

The Zoning Ordinance prohibits any activity from emitting "vibration" that "will adversely affect permitted used on an adjacent property" or activity that "emit[s] noise that is readily discernable to the average person in any adjacent residential zoning district." § 18.160 A and B. The Township's Master Plan further states that "[i]ndustries that traditionally cause excessive noise, vibration, odors, visual blight, environmental pollution, or are[] involved in potentially hazardous processes, should be avoided or allowed only on a discretionary basis." Master Plan, Page 55.

Data centers are notorious for their 24/7 buzzing noises and vibrations caused by their cooling systems.[1] The noise pollution from data centers impacts the physical health of people by causing permanent hearing loss, severe migraines, nausea, and even panic attacks.[2] Data Centers also adversely impact the environment by scaring away wildlife with their noises, causing significant pollution through the use of fossil fuels to meet their tremendous electricity demands, and using up between hundreds of thousands up to millions of gallons of water per day.[3]

Allowing the Parcel to be rezoned for a light industrial use for a data center violates the Zoning Ordinance's prohibitions on noise, vibrations, and environmental pollution and is inconsistent with the Township's Master Plan.

c. There will be no adverse effect on property values in the adjacent area.

Mr. Wells confidently implies in his Report that development of the Parcels by Microsoft will increase nearby home values over the long term. Even Microsoft in its Application does not make this bold claim. In fact, Microsoft argues that "[a]ny impact on property values would have already occurred." Regardless, it is unclear why Microsoft or Mr. Wells would make these claims without further research, information, or expert knowledge on property values.

Developing the Parcel into a data center will likely have an impact on property values, particularly the residential properties that both abut and are located across the roadway from the Parcel. However, data centers are relatively new, and there is not enough long-term data to make a sound determination if there will or will not be adverse effects on property values in the adjacent area.

Without further information, it cannot be claimed that Microsoft meets the Zoning Ordinance's standard here.

d. It will not create a deterrent to the improvement or development of adjacent property in accordance with existing regulations.

Mr. Wells claims in his Report that "[r]ezoning [the Parcel] to Light Industrial will have no effect on future development of the parcels to the west and south." However, yet again, Mr. Wells is ignoring that the parcels to the east and southwest of the Parcel are residential properties. Developing the Parcel into a data center will create a deterrent to improve or develop the adjacent residential parcels.

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[1] https://www.npr.org/2025/07/17/nx-s1-5469933/virginia-data-centers-residents-saying-no.
[2] https://www.aipowerweekly.com/p/how-bad-are-the-health-effects-of.
[3] https://www.bbc.com/news/articles/c93dnnxewdvo; https://www.staxengineering.com/stax-hub/the-environmental-impact-of-data-centers/.

As data centers cause signification noise and environmental pollution, individuals near the Parcels would likely want to leave, not improve, and/or not develop the adjacent residential properties.

3. The site is adequately served by streets and public utilities, and the rezoning will not impact the delivery of public services.

As stated earlier, data centers use tremendous amounts of water. A large data center can use up to five million gallons of water per day.[4] This incredible amount of water usage leads to depleted water resources which harms the community and environment at large.[5] In recent years, Michigan has faced unprecedented droughts and overall the state's watersheds are at risk of depletion.[6] Our community's and state's water supply would be at risk if these Parcels are rezoned and a data center is built on it.

Additionally, data centers use colossal amounts of electricity. In 2024, data centers located in the United States collectively used more electricity than the entire country of Pakistan.[7] The electricity consumed by data centers significantly strains the power grid and causes unreliability.[8] Across the United States, data centers have already caused numerous power outages, and that risk is only increasing.[9] A data center in our Township may strain the power grid and cause power outages.

Based on this information, if the Parcels are rezoned, the data center cannot be adequately served by public utilities and will impact the delivery of public services.

In conclusion, rezoning the Parcels is inconsistent with the Township's Zoning Ordinance. Additionally, the proposed data center would significantly and irreversibly harm the community and environment. As such, the Planning Commission should deny Microsoft's request to rezone the Parcels.

Additionally, the Township Board of Trustees should place a moratorium on making any decisions related to data centers for a minimum period of one year. This would allow the Township to conduct further information gathering on data centers (such as the impacts on

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[4] https://www.eesi.org/articles/view/data-centers-and-water-consumption.
[5] https://www.npr.org/2022/08/30/1119938708/data-centers-backbone-of-the-digital-economy-face-water-scarcity-and-climate-ris.
[6] https://www.theguardian.com/technology/2025/dec/16/great-lakes-us-data-centers; https://droughtmonitor.unl.edu/CurrentMap/StateDroughtMonitor.aspx?MI.
[7] https://www.pewresearch.org/short-reads/2025/10/24/what-we-know-about-energy-use-at-us-data-centers-amid-the-ai-boom/.
[8] https://www.pewresearch.org/short-reads/2025/10/24/what-we-know-about-energy-use-at-us-data-centers-amid-the-ai-boom/.
[9] https://www.reuters.com/technology/big-techs-data-center-boom-poses-new-risk-us-grid-operators-2025-03-19/.

<u>nearby home values, electricity and water usage, noise and vibrations emissions, etc.), public listening sessions, and create informed ordinances and regulations for similar developments.</u>

Respectfully,

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