


Review

Neurobehavioral Alterations in Occupational Noise Exposure: A Systematic Review

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Abstract: The psychology of sustainability and sustainable development emphasizes the value to ensure health and well-being in different environments, including workplaces. Chronic exposure to noise can cause several extraordinary effects and involve all the systems of the human organism. In addition to cardiovascular, gastrointestinal, and immune effects, the data in the literature show alterations in behavioral disturbances, memory capacity, and cognitive performance. Through this systematic review, the authors try to find out the main neurobehavioral alterations in the case of occupational exposure to noise. The literature review included articles published in the major databases (PubMed, Cochrane Library, Scopus, Embase), using a combination of some relevant keywords. This online search yielded 4434 references; after selection, the authors analyzed 41 articles (4 narrative reviews and 37 original articles). From this analysis, it appears that the main symptoms are related to psychological distress, annoyance, sleep disturbances, and cognitive performance. Regarding tasks, the most frequent employments concern school staff, followed by employees from various industrial sectors and office workers. Although the causes are still widely debated, it is essential to protect these workers against chronic exposure to noise. In fact, in addition to a hearing loss, they can manifest many other related discomforts over time and compromise their full working capacity, as well as expose them to a greater risk of accidents or absences from work.

Keywords: occupational noise; job; work; behavioral disorders; psychological disorders; annoyance; occupational medicine; prevention



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1. Introduction

The psychology of sustainability and sustainable development [1–3] is focused on health and well-being of individual/s in different environments. A healthy workplace, through sustainable culture, climate, and practices, create an environment that protects and boosts workers health and safety, as well as organizational effectiveness. Sustainable development can be considered a primary prevention that fosters well-being of the individual and the society. Considering this framework and the need for the development of sustainable workplaces, this systematic review aims to examine the main neurobehavioral alterations in case of occupational exposure to noise. Environmental exposure to high noise levels has been associated with mental health [4,5]. In fact, anxiety, emotional stress, nausea, headache, instability, sexual impotence, mood swings, increased social conflicts or general

psychiatric disorders such as neurosis, psychosis, and hysteria are frequent symptoms linked to important exposures to noise [6]. Furthermore, high levels of environmental noise can interfere with the central, peripheral, and autonomic nervous systems such as, for example, alarm reflex and orientation reaction, modifications of the EEG trace, increase in intracranial pressure, headache, and reduction of chronaxia [7].

From this evidence, it can be hypothesized that the extra-auditory effects of noise occur through a series of nervous circuits which, through the autonomic nervous system, act on the cardiovascular, gastrointestinal, endocrine, central nervous and immune system. These anatomical connections of the auditory pathways with the reticular formation may explain the effects of noise on the level of behavioral activation (arousal), pain, and sleep [8]. Besides, some neurobehavioral manifestations may be the consequence of changes in chemical transmissions.

For example, annoyance and sleep disorders are some of the most widespread and documented responses to chronic noise exposure [9–12]. Annoyance reactions are proportional to the degree of interference of noise in daily activities, but also to coping strategies, that is, to the ability of the subject exposed to noise to adaptively modify his or her own behavior in response to the auditory stimulus [13].

However, the hypotheses on the relationship between these phenomena and exposure to noise are controversial and widely debated. Through several major studies conducted to define the interactions between noise, annoyance, and mental disorders, Stansfeld concluded that ambient noise does not cause clinically defined psychiatric disorders [14]. Speedwell and Caerphilly also came to the same conclusion [15]. However, from the longitudinal results of the Caerphilly study, there is a weak and non-linear association between noise exposure and increased anxiety [6,16].

Nevertheless, it is necessary to consider how the extent and duration of the effects are determined in part by other variables, such as individual sensitivity, lifestyle, and environmental conditions [17,18].

Regarding jobs, the data in the literature show that occupational exposure to high and prolonged industrial noise can lead to alterations in psychomotor tests, decreased reaction times to acoustic and visual stimuli [19], cognitive deficits, especially affecting the memory function [20–22], and alterations in attentional capacity [12,21,23,24]. Moreover, other characteristics of noise, such as frequency, duration of exposure, and interruptions in the exposure can be relevant for the effects of the noise on human well-being. For example, irregular or pulsating noises can be more annoying than a steady noise: intensity alone is not an adequate parameter to describe noise exposure, especially when it comes to neurobehavioral effects. In addition, noise exposure can cause neurobehavioral effects indirectly—for example, causing distraction or difficulties in interactions between people. The purpose of this systematic review is to explore the interferences of noise on human neurobehavior. In particular, it aims to define what neurobehavioral alterations can occur in workers exposed to occupational/workplace noise and possible association and risk factors. Since a literature review exploring the extra-auditory effects of the exposure to occupational noise was conducted in 2011 [25], this review aims to collect scientific evidence of the last 10 years. Restricting the search to the last 10 years will reduce the heterogeneity of studies and the possible bias, considering the technical and legislative progress made to reduce occupational noise in the last decade [26].

2. Materials and Methods

This systematic review follows the Prisma Statement [27].

2.1. Literature Research

The research included articles published in the last 10 years, from 2010 to 15 September 2020, on the major online databases (PubMed, Cochrane Library, Scopus, Embase, Google Scholar). The search strategy used a combination of controlled vocabulary and free text terms based on the following keywords: work, job, task, workplace, noise, loud,

sound, occupational, environment, neurobehavioral, psychological, mental, neural. All research fields were considered. The search string used was the following: (((((noise) OR (sound)) OR (sound level)) OR (loud)) AND (((((((workplace) OR (work)) OR (job)) OR (job task)) OR (occupation)) OR (occupational)) OR (environmental)) OR (environment))) AND (((((((neurobehavioral) OR (behavioral)) OR (behavioral)) OR (neurobehavioral)) OR (psychological)) OR (mental)) OR (neural)).

In particular, we conducted a research strategy in the databases on the effects of noise exposure on workers' health by applying the PICO statement. The population studied was that of workers, with no difference in age, gender, or type of job. The type of intervention concerned any type of noise exposure in the workplace. The health outcomes considered were those related to neurobehavioral changes second the most recent studies. We included short-term effects and medium- to long-term effects, such as insomnia, sleep, fatigue, impaired concentration and memory, changes in work performance, errors, mood changes with irritability, anxiety, aggression, depression, annoyance. If found, physiological measures and work–life balance, such as hormone excretion level or changes in management of social and family life, were included.

The pre-specified search terms of PICO are focused upon in Table 1.

Table 1. PICO statement.

Population	((workplace) OR (work*) OR (job)) OR (job task)) OR (occupation)) OR (occupational)) OR (environmental)) OR (environment)
Interventions	((noise) OR (sound)) OR (sound level) OR (loud)
Comparison	N.A.
Outcomes	((neurobehavioral) OR (behavioral)) OR (behavioral)) OR (neurobehavioral)) OR (psychological)) OR (mental)) OR (neural))

Additionally, we practiced a manual search on reference lists of the selected articles and reviews to carry out a wider analysis. Two independent reviewers read titles and abstracts of the reports identified by the search strategy. They selected relevant reports according to inclusion and exclusion criteria. Doubts or disagreements were solved by discussion with a third researcher.

Subsequently, they independently screened the corresponding full text to decide on final eligibility. Finally, the authors eliminated duplicate studies and articles without full texts.

Data were mainly obtained from the published results but also from any other supplementary sources when these were available. In particular, the authors selected date and country of publication, sample size, involved noise source, exposure decibel, and kind of reported disorders. In addition, the authors highlighted the number of studies included for all reviews and the length of the study in the case of experiment or cohort studies.

2.2. Quality Assessment

Three different reviewers assessed the methodological quality of the selected studies with specific rating tools, to reduce the risk of introducing any bias. We used the INSA method “International Narrative Systematic Assessment” to judge the quality of narrative reviews [28], AMSTAR to evaluate systematic reviews, and the Newcastle Ottawa Scale to evaluate cross-sectional, cohort studies, and case control studies [29,30], while we applied the Jadad scale for randomized clinical trials [31]. In addition, to reduce the risk of bias, we used RobVis (BARR, Bristol, UK), a specific tool for systematic reviews [32] (see Appendix A Figures A1 and A2).

2.3. Eligibility and Inclusion Criteria

As stated by the PICO scheme above, the studies included in this review focus on occupational noise and professional categories exposed to this risk. Studies considering workers exposed to environmental noise in the workplace are also included. The studies included refer to occupational noise, measured through quantitative and qualitative assess-

ment. We included studies on principal neurobehavioral consequences to this exposure, in particular annoyance, sleep disorders, short memory, poor concentrations, and working performance. All types of study designs were included. No restrictions were applied for language or country.

2.4. Exclusion Criteria

We excluded reports related only to environmental exposure or noise pollution, not specifically conducted in a workplace setting, publications on programmatic interventions, and studies not considering diseases or disturbances linked to noises. We restricted our search to the last 10 years, as explained in the Introduction. We also excluded reports of less academic significance, editorial articles, individual contributions, and purely descriptive studies published in scientific conferences, without any quantitative and qualitative inferences.

3. Results

The online search yielded 4485 studies: PubMed (3056), Scopus (21), Cochrane Library (13), Embase (115), Google Scholar (1280). Of these, 4434 studies were excluded because they were deemed unrelated to noise-related problems. Among the remaining studies, four articles were also excluded because they were duplicates. Duplicate publications were carefully eliminated in order not to introduce bias, by comparing the names of the authors, the topics addressed, the workers examined, and the results obtained. Another six publications were deleted because the full text was not available. In conclusion, 41 studies were finally included in this analysis (Figure 1). Of these, 4 are literature reviews (2 systematic; 2 narrative) and 37 are original articles. Among the latter, 16 are cross-sectional studies, 2 cohort studies, 5 case control studies, 2 pilot studies, 1 observational study, 10 experimental studies, and 1 mixed (cross / experimental) study (Table 2).

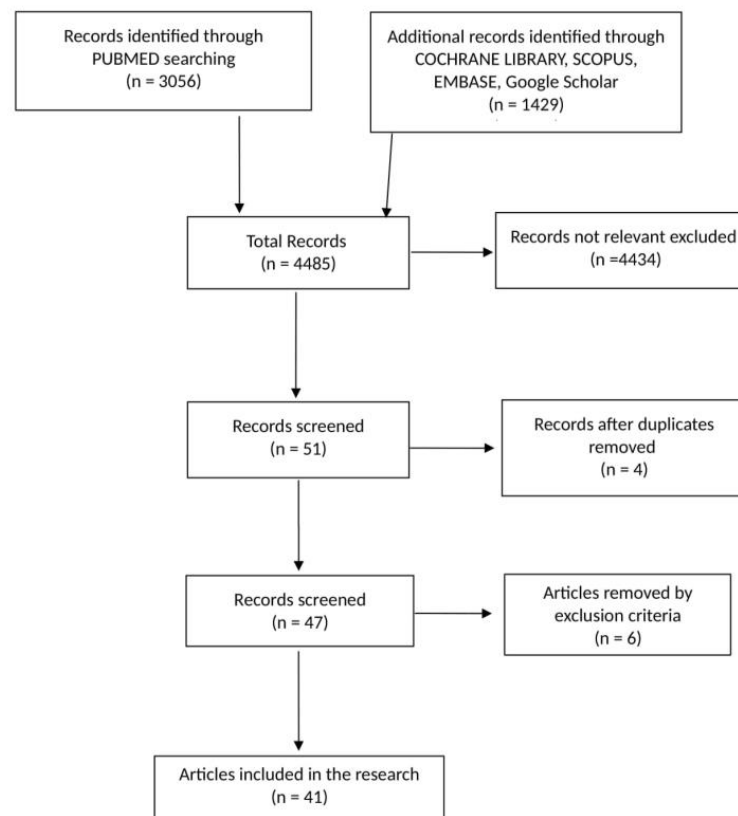


Figure 1. Flowchart of bibliographic research.

Table 2. Studies including in this systematic review, in alphabetical order.

First Author	Year	Country	Study	Categories Workers	Diseases
Abbasi	2015	Iran	pilot study	wind farmers	general health, sleep disorders, annoyance
Alimohammadi	2019	Iran	case control	automotive workers	cognitive performance, annoyance
Alimohammadi	2018	Iran	cross-sectional	automotive workers	aggressive behavior
Alimohammadi	2010	Iran	cross-sectional	white collar employees	annoyance
Azuma	2017	Japan	cross-sectional	office workers	psychological distress
Burns	2019	USA	cross-sectional	electronic waste workers	perceived stress
Cheng	2019	China	case control	military	working memory performance
Clausen	2013	Denmark	cohort study	office workers	long-term sickness absence
Deng	2019	China	cross-sectional	not specified	depression
Di Blasio	2019	Italy	cross-sectional	office workers	annoyance, mental health, well-being
Eysel-Gosepath	2012	Germany	cross-sectional	teachers	annoyance, sleep disorders, fatigue
Fredriksson	2015	Sweden	cross-sectional	obstetrics	annoyance, work-related stress
Fredriksson	2019	Sweden	cohort study	teachers	work-related stress
Freiberg	2018	Germany	systematic review	wind industries	annoyance, sleep disorders
Habibi	2013	Iran	experimental study	university personnel	speed of work, annoyance
Horsten	2018	Netherland	systematic review	healthcare workers	sleep disorders
Hua	2014	Sweden	case control	employees	cognitive skills
Irgens-Hansen	2015	Norway	experimental study	navy personnel	cognitive performance
Jahncke	2011	Sweden	experimental study	open-plan offices	cognitive performance
Keller	2017	USA	experimental study	military	cognitive performance
Keller	2018	Switzerland	observational study	healthcare workers	cognitive performance
Kim	2016	Korea	cross-sectional	office work, sales, manufacturing	smoking intensity
Kristiansen	2014	Denmark	cross-sectional	teachers	mental health, fatigue
Mahendra Prashanth	2011	India	narrative review	industrial workers	sleep disorders, cognitive performance
Mapuranga	2020	Zimbabwe	cross-sectional	manufacturing workers	job performance
Milenovic	2018	Serbia	case control	manual/administrative workers	aggressiveness
Molesworth	2015	Australia	experimental study	aircraft personnel	recognition memory, working memory, reaction time
Monteiro	2018	Portugal	pilot study	students/fast food employees	working memory performance
Nari	2020	Korea	cross-sectional	employees	sleep disorders
Oenning	2018	Brazil	cross-sectional	various (public, private, domestic, farmworkers, technicians, managers)	depressive disorders
Onchang	2018	Thailand	case control	university personnel	annoyance
Realyvásquez	2016	Spain	experimental study	manufacturing workers	working performance, job satisfaction, aggressivity
Schlittmeier	2013	Germany	cross/experimental study	office workers	cognitive performance, annoyance
Sjodin	2012	Sweden	cross-sectional	preschool personnel	work-related stress, sleep disorders
Sloof	2010	Netherland	experimental study	university personnel	work motivation
Smith	2010	UK	experimental study	university personnel	working memory performance
Tomic	2018	Sweden	experimental study	not specified	working memory performance
Wassermann	2013	USA	case control	university personnel	attention
Wright	2016	UK	experimental study	university personnel	cognitive performance, psychological disorders
Yoon	2014	Korea	cross-sectional	white, pink, blue collars	depressive disorders, suicidal ideation, annoyance
Yuen	2014	Malaysia	narrative review	manufacturing workers	annoyance, sleep disorders

Sweden is the country where most of the studies were published (6/41; 14.6%). Most of the articles were published in 2018 (9/41; 21.9%), followed by 2019 (6/41; 14.6%).

We used the VosViewer tool to create a bibliographic map of the articles retrieved [33]. Figure 2 shows the keywords' co-occurrence network of the articles in the sample. Node sizes are proportional to how many articles are labeled with the keyword selected. Two nodes are connected if the respective keywords are co-associated in an article. The restriction to generate the network is that each keyword occurs almost three times; 36 terms were identified and the total strength of the co-occurrence links with other keywords were calculated. The term "human" was excluded from the network map because all the studies considered have humans as subjects. The network map shows three clusters of keywords' co-occurrence. The major disturbances linked to noise are "depression," "psychological stress," "hearing loss," which are associated with "occupational disease" and have a link to the keyword "middle aged." The cluster shows keywords such as "cross-sectional studies," "prevalence," and "risk factors," suggesting the type of prevalent studies in the selected articles. Moreover, "surveys and questionnaires" seems to be the most used tools in the investigations (cluster red on the right side). "Attention," "short-term memory," and "task performance" are the other keywords shown on the map and linked to "occupational noise" and "transportation noise" (cluster green on the left). Cluster blue on the top groups' keywords related to work environment makes a connection between ergonomics, noise, and work performance.

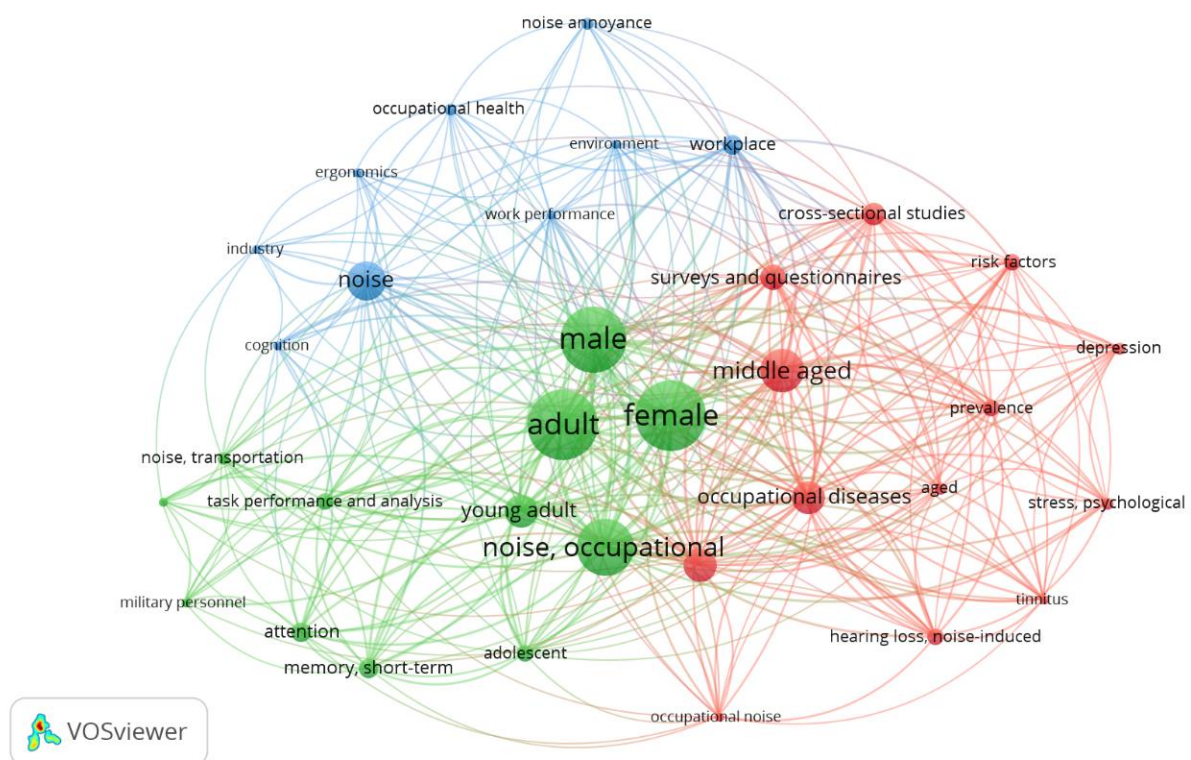


Figure 2. Network map of co-occurrence keywords.

Selected articles examine various symptoms related to psychological distress and reported by the samples, such as annoyance (11/41; 26.8%), sleep disturbances (9/41; 21.9%), and reduced work/cognitive performance (14/41; 34.1%). Taking into consideration the tasks examined, it was found that the most frequent analyses concern school staff (10/41; 24.3%), followed by employees from various industrial sectors (9/41; 21.9%) and office workers (6/41; 14.6%).

3.1. Narrative and Systematic Reviews

Regarding the methodological quality of the systematic reviews, the AMSTAR scores show an average, a median, and a modal value of 9, indicating the high quality of the studies (Table 3). Regarding narrative reviews scores, the INSA score shows an average and a median value of 5.5, indicating an intermediate quality.

Table 3. Reviews included in this article, with their relative score.

First Author	Included Articles	Results	Score
Freiberg	20	Exposure to onshore wind turbine noise leads to annoyance, sleep disorders, and lowered general health.	A.9
Horsten	20	Effect of noise on sleep in the ICU seems to have a significant effect on the arousals in six studies performed with healthy volunteers. The majority of the observed arousals remain unexplained because they did not occur within 3 s of a sound peak.	A.9
Mahendra Prashanth	narrative	The data suggest that significant adverse health effects due to industrial noise include auditory and heart-related problems. The study provides strong evidence for the claims that noise with a major frequency characteristic of around 4 kHz has auditory effects and being deficient in data fails to show any influence of noise frequency components on non-auditory effects.	I.5
Yuen	narrative	Results from the survey, monitoring, short-term, and longitudinal studies have positioned the noise pollution scenario in Malaysia at a critical level. This highlighted the resurgent need of practical solutions by the government, non-governmental organizations, and educational institutions to generate a healthy working and living environment.	I.6

However, each of these reviews analyzed different work environments, with different complaints reported by workers.

For example, topics covered by Freiberg et al. [34] included some job duties involving wind turbines (manufacturing, transportation, installation, operation, and maintenance). The study population, however, was composed not only of workers in the wind industry, but also of others who worked around wind farms. The literature showed how the noise of wind turbines had a significant influence on the development of annoyance, daytime sleepiness, and general health problems among workers; moreover, even the workers in other sectors but within 3 km of the turbines show a certain prevalence of disorders attributable to this source of noise [35].

Horsten et al., on the other hand, analyzed the scientific evidence of the effect of noise in ICUs on sleep quality. They showed that such noise in the ICU has a significant negative effect, with increased arousals in six studies performed with healthy volunteers; however, there is a high risk of bias due to the multifactorial nature of sleep disorders in intensive care, the different protocols implemented by the different experiments, the sound levels not always measured, and finally the administration of questionnaires not always standardized with subjective symptoms [35].

Mahendra's review focuses on studies published between 1988 and 2009 on the effects of industrial noise, analyzing auditory and non-auditory effects. Some of his included studies have shown that with lasting exposures between 43 and 73 Hz, particular disturbances can occur, such as lack of visual acuity, a drop in IQ scores, distortion of spatial orientation, poor muscle coordination, loss of balance, and confused speech. However, specific noise levels in terms of frequencies that predict health impacts have not yet been validated [25].

Finally, in the case of exposure to vehicular traffic, Yuen highlighted how the discomfort associated with continuous exposure to traffic noise can create an unpleasant condition in highway toll workers and residential communities in the surrounding areas. Traffic noise levels are typically between 75 and 85 dBA and occasionally reach 90 dBA. Respondents wake up more often, have had poorer sleep quality, and feel sleepy during their day work. In addition, they negatively assessed the installation of the so-called TRS "crossroad strips,"

as they generate excessive vibrations and pulsating or impulsive noises, similar to the sound of hammers, firecrackers, or small explosions [36].

3.2. Original Articles

The scores assigned to the original articles have an average value of 5.16, a mode of 7, and a median of 6; this indicates an intermediate quality of the studies (Tables 4 and 5).

Researchers from Iran, China, Japan, Sweden, Korea, Denmark, Serbia, Brazil, Thailand, Zimbabwe, and USA have obtained the highest values (NEW CASTLE Scale = 7). Sweden remains the country where the most articles related to the topic have been published in the last 10 years (6/37; 16.2%), followed by Iran (5/37; 13.5%).

To carry out the results and considering the quantity of the selected articles, we proceed with a synthesis of the results based on the main disorders and workers' categories found by the authors.

3.2.1. Main Disorders

The main disorders analyzed include cognitive performance, attention, and motivation in the workplace (15/37; 40.5%), followed by annoyance (4/37; 10.8%), stress (3/37; 8.1%), mood changes with depression and/or aggression (2/37; 5.4%), sleep disturbances (1/37; 2.7%). Finally, six articles (6/37; 16.2%) analyze multiple disorders (for example, depression and annoyance, stress and sleep, stress and annoyance, sleep and annoyance, and cognitive performance and annoyance).

As for the questionnaire administered to workers, some authors investigate aspects concerning general health, through questionnaires such as General Health Questionnaire (GHQ) and Patient Health Questionnaire (PHQ), or work-related stress, through effort-reward imbalance (ERI), Perceived Stress Scale (PSS), and Copenhagen Psychosocial Questionnaire (COPSOQ). Other studies evaluate work performance more specifically, for example, through the Stroop test (ST), reaction time (RT), memory test, and the sustained attention to response test (SART).

Regarding cognitive functions or various logic and memory skills, most authors agree that their quality decreases with exposure to noisy sources. For example, Alimohammadi proved that all the cognitive indicators have a significant relationship with exposure to noise, but in all the cognitive indicators annoyance does not have a significant relationship with cognitive performance [37]. In the study by Monteiro et al., people tested for memory, attention, and serial recall tended to make more mistakes as the noise intensity increased. The participants experienced growing discomfort, stress, and annoyance as the sound pressure levels increased ($p < 0.05$) [38]. Better cognitive performance can be related to higher education and younger age [39].

For Cheng, the effects of noise can be traced with magnetic resonance imaging. Exposure group scored worse on mental tests, and they had less brain gray matter volumes in the left hippocampus, right middle frontal gyrus, and right inferior parietal lobule compared with the control group ($p < 0.002$, $p < 0.05$). The same group showed significantly lower regional homogeneity values in the left amygdala, left hippocampus, left thalamus, and right middle/superior frontal gyrus ($p < 0.01$) [40].

However, other authors have found conflicting information; for example, Wassermann found that the participants' reaction times are slower in the control condition than in the pink and TV sitcom noise conditions. So, complex television noise does not impair attention, while pink noise, or a signal that combines relevant frequencies, does [41]. For Keller, speech intelligibility has a relevant role in communication; in fact, as the speech intelligibility goes down, missed communication rate and requests for repeat backs increase ($p < 0.001$). Communication errors in some tests were significant in relation to the decrease in speech intelligibility. However, overall eye behaviors were not overly impacted by the different speech intelligibility levels (eye blink rates, pupil dilation, and basic measures of saccade and fixation metrics showed no difference with increased fatigue, strain, and noise levels) [42].

Table 4. Cross articles included in this review, in alphabetical order, with their relative score.

First Author	Included Subjects	Exposure's Range	Questionnaire/Tests	Results	Score
Alimohammadi	250	70–90 dB	Buss and Perry's questionnaire	There was a significant ($p < 0.05$) correlation between the measured noise intensity and the aggression level.	N.7
Alimohammadi	495	LEPd 65.05	WNSS, SAS, EPI, AQ, BDI	Noise annoyance among people who reported their workplace as high in ambient noise is 4.05 times more than that among other people.	N.7
Azuma	489	not specified	MM40, JSQ	Carpeting, unpleasant chemical odors, noise, dust, and dirt were significant risk factors for BRSSs.	N.7
Burns	46	78.8 ± 5.9 dBA	PSS	Perceived stress level and perceived noise exposure were associated with a significantly greater number of injuries.	N.6
Deng	106	not specified	ZSDS, PSQI	Higher depressive status was positively correlated with THI score, PSQI score, and duration of occupational NIHL.	N.6
Di Blasio	1078	not specified	not validated	Irrelevant speech increases noise annoyance, decreases work performance, and increases symptoms related to mental health and well-being more in open-plan than in shared offices.	N.6
Eysel-Gosepath	43	65–87 dB	not validated	Teachers experience the highest sound levels in the schoolyard, corridors, and classrooms, and 68% of the teachers are annoyed by the noise.	N.5
Fredriksson	115	56–87 dB Laeq	ISO/TS 15,666	Work-related stress and noise annoyance at work were reported by almost half of the personnel. Sound-induced auditory fatigue was associated with work-related stress and noise annoyance at work.	N.7
Kim	3769	not specified	KNHANES VI-3	Dirty workplace and exposure to occupational noise are significant factors increasing the smoking intensity for manufacturers.	N.7
Kristiansen	35	61.8–83 dB	SEI, SART, TBT	Change in TBT performance also showed a moderate correlation with the teacher's average noise exposure, in particular when limiting the analysis to general classrooms ($p = 0.11$).	N.7
Mapuranga	250	not specified	not validated	Occupational noise had a positive and significant effect on attitudes towards occupational exposure and perceived susceptibility to hearing loss among manufacturing workers.	N.7
Nari	30,837	not specified	KWCS	OR of insomnia due to noise exposure was 1.10 and 1.07 in men and women, respectively. For noise plus vibration exposure, OR was 1.83 in men and 3.14 in female workers.	N.7
Oenning	60,202	not specified	PHQ9	Associations of chemical substances and noise with MDD were found to be significant among women only (the two interaction terms were significant at $p < 0.05$).	N.7
Schlittmeier	74	35–55 dB	not validated	Background speech is subjectively perceived as a severe problem, and the different noise abatement measures affect objective performance and subjective ratings differently.	N.7
Sjodin	101	71 Laeq mean	SOFI, ERI, KSS, SMBQ	Stress and energy output were pronounced among the employees, and about 30% of the staff experienced strong burnout syndromes.	N.7
Yoon	10,020	not specified	not validated	Compared to the no noise annoyance group, ORs of the severe annoyance groups were 1.58 and 1.76 in men and 1.49 and 1.41 in women for depressive symptoms and suicidal ideation, respectively.	N.7

Table 5. Cohort/case control/pilot/observational studies in alphabetical orders, with relative scores.

First Author	Included Subjects	Exposure's Range	Questionnaire/Tests	Length	Results	Score
Alimohammadi	150 cases/150 controls	38–46; 82–88	Stroop test, London Tower test	not specified	A significant correlation between the workers' cognitive performance and annoyance levels (p value < 0.001).	N.6
Abbasi	53	60–83 dB	GHQ28, ESS, ISO TS 15,666	not specified	Wind turbines noise can directly impact on annoyance, sleep, and health. This type of energy generation can have potential health risks for wind farm workers.	n.a.
Cheng	30 cases/30 controls	not specified	fMRI	not specified	Reduced ReHo in the left amygdala, left thalamus, left superior temporal gyrus, and right superior/middle frontal gyrus, indicating disrupted local neural activity under chronic noise exposure.	N.7
Clausen	2883	not specified	RSS register	1 year	Office workers who reported being “frequently” exposed to disturbing noise had a significantly increased estimated risk of LTSA.	N.6
Fredriksson	4718	not specified	ERI, COPSQ	6 months	Preschool teachers had overall more than twofold RR of sound-induced auditory fatigue (RR 2.4) and hyperacusis (RR 2.3) and almost twofold for difficulty perceiving speech (RR 1.9). RR and IRR were generally still increased for preschool teachers when stratified by age and occupational exposure to noise and stress.	N.6
Hua	20 cases, 20 controls	not specified	cognitive tests, SART	2010–2012	Noise generates a significantly higher PE and brings explicit processing capacity into play, irrespective of hearing.	N.6
Keller	110 surgeries	53–57 dB	not validated	367 h	Adjusted for duration, surgical type, and difficulty of the surgery, results showed that second surgeons are more likely distracted when noise pollution is high in the main phase, and anesthetists are more likely distracted when noise pollution is high during the closing phase.	N.6
Milenovic	60 cases, 60 controls	70–90 dB; < 55 dB	SIGMA	not specified	A tendency for reactive aggressiveness increases with noise intensity, at least in cases of the 70–90 dB interval.	N.7
Monteiro	15	45 ± 0.3 dB(A), 60 ± 0.4 dB(A), 68 ± 0.4 dB	serial recall, response inhibition, Stroop interference	a weekend	Number of errors was higher and the reaction time longer, with increased noise levels.	n.a.
Onchang	786	58.3–72.4 Leq24 h	International Commission on Biological Effects of Noise	not specified	Off-campus student cohort was, however, more annoyed by all community noise categories (p < 0.001) except road traffic noise.	N.7
Wassermann	27	not specified	PCT	not specified	Attention was significantly improved in pink noise compared to the ambient noise, whereas no differences were found between the ambient and television conditions.	N.7

Another disorder frequently found in the selected articles is annoyance. Some authors have looked for a correlation between this reported symptom and some individual or work-related factors. For example, Yoon found a difference between gender (ORs 1.58 for men, 1.49 for women with depression, and 1.41 for women with suicidal ideation) and sleep time (ORs 2.95 for workers with less than five hours of sleep) [43].

Moreover, the workplace is important. In fact, Di Biasio showed that workers in shared offices are less annoyed than those who work in open-plan offices. In this last group, he observed a difference between gender (women are more annoyed), year range (51–65+ are more annoyed), and type of workplace (those who work in sales or public affairs sectors or engineering and teaching sectors are more annoyed) [44]. Additionally, a very noisy environment can lead to hearing fatigue and tinnitus, which in turn are related to work-related stress and annoyance [45].

Finally, annoyance is related to individual sensitivity. In fact, for Alihommadi, noise annoyance is significantly related to noise sensitivity ($p = 0.0015$). People with higher level of noise sensitivity were more annoyed than those with moderate (OR = 11.78) and low sensitivity (OR = 4.88). Moreover, medium level of anxiety seemed to worsen noise annoyance, while in individuals with either low or high level of anxiety, noise annoyance was lower ($p = 0.005$) [46].

We found many other types of neurobehavioral disorders with noise exposure. For example, Azuma found three more frequent general symptoms, such as “tension, irritability, or nervousness,” “feeling depressed,” and “unusual tiredness, fatigue, or drowsiness” [47]. Besides, in Sjodin’s study, preschool personnel described their occupational fatigue at midday in terms of lack of energy and motivation, physical discomfort, and sleepiness at work. These employees reported being more tired before going to sleep ($p < 0.05$). Higher levels of depression were related to higher sound fluctuation as perceived subjectively ($p < 0.05$) and the assessed morning cortisol correlated positively with noise annoyance during work ($r = 0.284$, $p < 0.05$) [48].

Mood swings were also found in the Oenning’s and Deng’s study; in fact, they found an association between chemical substances and noise with depressive symptoms among women belonging to various work categories ($p < 0.05$). Sometimes, depressive symptoms are secondary to hearing loss caused by exposure to noise and subsequent isolation [49,50].

Insomnia is another ailment reported by workers. In his study, Nari found an increased risk of developing this discomfort in both genders, especially if exposed to vibrations at the same time (1.83/ CI 1.61–2.07 in men and 3.14/ CI 2.76–3.57 in women) [51]. Sleep disturbances appear to be triggered by annoyance, which in turn is related to noise exposure, but they do not appear to be related to the age of workers [52].

Another interesting fact is the finding of a greater tendency to develop aggression when exposed to noisy sources. In his study, Alihommadi found that it is present a positive correlation between the daily dose of noise received by the workers and aggressive behavior in terms of verbal and physical aggression, hostility, and anger ($p < 0.05$) [53]. Furthermore, Milenovic showed that a tendency for reactive aggressiveness increases with noise intensity, in particular between 70 and 90 dB ($p < 0.01$); he also noted that length of employment did not affect levels of aggressiveness [54]. These conditions can cause workers to show a greater predisposition to addiction. For example, Kim discovered increased intensity of cigarette smoking in noisy and safety-threatening workplace environments [55]. Finally, a higher rate of occupational injuries has been related to greater perceived noise exposure in electronic waste recycling workers of low-income countries [56].

3.2.2. Type of Workers

School staff is the main categories of workers analyzed in original articles (11/37; 29.7%), following by various employees (industry, farmers, manufacturing, etc.) and office-administrative workers (7/37; 18.9%), military personnel (4/37; 10.8%), healthcare workers (2/37; 5.40%).

Among school staff, the variable factors that can correlate with a greater manifestation of neurobehavioral disorders are working age, hours of lessons, and workload. For example, in Eysel's study, sleep disturbances in teachers older than 45 years of age were common; tiredness and exhaustion in the evening, after a full day of work, was present in almost all the employees (90%). In this context, 51% of the whole sample consider work as a physical and mental strain; older teachers report a significant worsening in these affectations with increasing years of professional activity in 81% of the cases [57]. Furthermore, in Fredriksson's study, symptoms generally occurred more often in older people ($p < 0.05$), excepting for hyperacusis and sound-induced auditory fatigue. The prevalence of such disorders increases significantly in people exposed to both noise and stressful working conditions compared to those unexposed ($p < 0.05$) [58].

The duration of exposure may influence the association between noise and symptoms. In Kristiansen's study, cognitive tests exhibited little changes when teachers with less than four lessons were excluded from the analyses. Moreover, the teachers' average noise exposure was moderately correlated with changes in TBT (two back test) performance, in particular when the analysis was limited to general classrooms (Spearman's $\rho = -0.35$, $p = 0.11$); instead, the scores in the sustained attention to response test (SART) did not correlate significantly with noise exposure or vocal load [59].

Finally, remaining in the school environment, even students can report related symptoms. Onchang found a difference between two students' cohorts, "the off-campus" (OG) and "inside-campus" (IG); the first suffered more than the others from all community noise categories (traffic, construction, recreation, and advertising; $p < 0.001$). The largest differences between the two groups in the perception of noise annoyance were consistently found for telephone and personal communication for all the types of community noise; conversely, the smallest differences were for listening to radio and television, reading, and mental tasks. In the group of OG students, reading and mental tasks significantly influenced cumulative grade point average (OR = 2.801, $p < 0.05$) [60].

3.3. Experimental Studies

We found 10 experimental studies (10/37; 27%). Iran, Norway, USA, Spain, Netherlands, Sweden have obtained the highest value (Jadad scale = 3) (Table 6). Below are some peculiarities found in this analysis.

In his experimental study, Irgens-Hansen evaluated cognitive performance under exposure to various noise levels among personnel working on board ships in the Royal Norwegian Navy. Reaction times were significantly higher in personnel exposed to values greater than 85.2 dB(A) and in the exposed group in the range of 77.1–85.2 dB(A), compared to personnel exposed to values below 72.6 dB(A). Furthermore, the latter reported a lower workload. Caffeine consumption and nicotine use did not differ significantly between the noise exposure groups [61].

The Molesworth study explored the effect on memory and psychomotor performance in being exposed to 75dBA broadband noise (simulation of an airplane cabin noise). When the performance of reaction times in the presence of noise was compared with conditions in which the volunteers had consumed alcohol, it was found that the impact of alcohol on reaction time was more severe than the noise itself [62].

Jahncke designed an experiment with the exposure of the 47 subjects tested in four different conditions (projecting films on nature, listening to the sounds of nature, with silence and with high/low noise). By testing memory capacity, participants scored lower when exposed to higher noise. Furthermore, the analysis revealed a significant interaction between noise and fatigue/lack of motivation: participants who viewed the film reported more energy than participants exposed to noise only ($p < 0.01$) and those who listened to the sounds of the nature ($p < 0.05$). Participants exposed to noise during the rest period ranked as less motivated (i.e., more disinterested) than participants who listened to the sounds of the river ($p < 0.05$) or watched the film ($p < 0.01$) [63].

In Smith's study, too, the beneficial role of music is highlighted. In fact, when participants are exposed to office noise, they exhibit lower performance alterations, although after a 10 min habituation period, their performance tends to improve. In the second part of the experiment, the author showed how instead an exposure to Mozart's works improved subsequent performances, especially as regards the visual-spatial reasoning activities [64].

Table 6. Experimental studies included in this review, with their relative score.

First Author	Subjects	Exposure	Length	Results	Score
Habibi	96	65, 85, 95 dB	0, 20, 40 min	Increasing sound pressure level from 65 to 95 dB in network "A" increased the speed of work ($p < 0.05$). Male participants got annoyed from the noise more than females. Moreover, increase in sound pressure level increased the rate of error ($p < 0.05$).	3
Irgens-Hansen	87	<72.6 dB(A), 72.6–77.0 dB(A), 77.1–85.2 dB(A), >85.2 dB(A)	14 months	Response time was significantly increased among personnel exposed to >85.2 dB(A) and 77.1–85.2 dB(A) compared to personnel exposed to <72.6 dB(A).	3
Jahncke	47	39–51 dB	some hours	Participants remembered fewer words, rated themselves as more tired, and were less motivated with work in noise compared to low noise; those who saw a nature movie (including river sounds) rated themselves as having more energy after the restoration period in comparison with both the participants who listened to noise and river sounds. Remaining in office noise during the restoration phase also affected motivation more negatively than listening to river sounds or watching the nature movie.	2
Keller	36	75 dB	some hours	Noise (and its effect on speech intelligibility) can have a significant negative impact on how well sailors are able to communicate, especially in a dynamic and high-stress environment.	3
Molesworth	32	75 dB	some hours	Participants completed three different tests (recognition memory, working memory, and reaction time) in the presence of noise, with or without noise attenuation headphones, and without noise but with a BAC of 0.05 or 0.10. Simulated aircraft noise was found to affect recognition memory but not working memory or reaction time.	2
Realyvásquez	158	not specified	not specified	Noise and lighting have no direct effects on employees' performance, but they do have direct effects on psychological characteristics, which in turn impact employees' performance. Environmental variables combine their effects on psychological characteristics that cause an impact on employees' performance.	3
Sloof	94	not specified	80 min	Subjects in the volatile environment are more strongly influenced by the presence of noise. More noise not only leads to a stronger stimulus to work, but also has a demotivating impact. On the one hand, more noise weakens incentives because the impact of effort on compensation becomes smaller relative to the impact of noise; on the other hand, noise strengthens effort incentives because subjects are more motivated to attain a certain (minimum) income target.	3
Smith	36–34	65 dB	some hours	Office noise can disrupt performance on working memory tasks (i.e., mental arithmetic) but that this disruption can be habituated to after a period of time in noise.	2
Tomic	31/11	not specified	not specified	Increasing internal noise released resources that could be used to store other stimuli more precisely; increasing external noise had no such effect on memory.	3
Wright	54	30–78 dB	40 min	They found significantly slower psychomotor speed (urban), reduced working memory and episodic memory (urban and social), and more cautious decision-making (executive function, urban) under noise conditions.	2

4. Discussion

The aim of this work was to analyze the most recent scientific literature to identify a correlation between exposure to noisy sources and the development of neurobehavioral disorders, particularly in the workplace. All the studies included defined the exposure to noise as related to the occupational setting, both as noise coming from the work procedures and noise coming from the environment in which the workplace is located.

First of all, our results actually highlighted a not very large number of articles; this could indicate a still current difficulty in approaching this complex issue. A significant amount of data in the scientific literature, in fact, concerns the already known effects of noise on the human body, such as those manifested by the cardiovascular system, and even to a lesser extent the insights into neurobehavioral disorders. After that, in our review, several publications and in particular the experimental studies, concerned working sectors in which they must pay a lot of attention and concentration in every procedure they perform, such as for example military personnel or surgical teams. This observation did not surprise us; in fact, tasks that require continuous and careful monitoring of signals (e.g., warning or alarm systems) can in fact be negatively affected by noise and can be used in experimental studies.

The studies available on the effect of noise in the workplace show how this risk can negatively affect the performance of certain activities, acting in particular on the level of performance and safety; for this reason, even accidents and injuries can be a sentinel indicator of a decline in performance [59,65,66], as well as distraction errors [67] or sickness absence among workers [68].

Exposure to noise can be reduced memory capacity [69–71] and short periods of inefficiency/unproductivity [72,73], especially when prolonged visual attention is required [74,75]. However, the evidence of the negative effects of noise on productivity in the workplace is still unclear and controversial. For example, a relationship between sound pressure levels and work productivity has not yet been demonstrated and some publications show opposite results, such as Habibi's experiment, where increasing the exposure noise increased (instead of decreasing) the speed of execution of some works [76]. Other studies indicate that absence from work is also associated with several variables to consider, such as gender, age [77], and smoking behavior [78].

Another working sector most examined in our analysis is that concerning the school staff. The noise in school classrooms originates from external sources, such road traffic, and from internal sources such as operators and pupils [79]. In noisy and reverberating classrooms, school-age children experience greater difficulties in both language perception and listening than adults [80–82]. The performance at school of children can be negatively affected by environmental noise, creating interferences in pupils' attention and motivation [83,84], disturbing reading comprehension [85,86], short-term memory [86,87], mathematical skills [88,89], and inducing some kind of hyperactivity [89,90].

These aspects can be decisive in children, as they interfere with language learning processes and phonation: they can favor the onset of dysphonia and dyslexia phenomena due to lack of or reduced control of phonation [91].

Several studies have analyzed the effects of exposure to environmental noise in children, relating to learning, the degree of interest, motivation, and stimulus. For example, research on school-age populations residing near European and international airports showed that they were unable to perform some difficult and complex tasks as well as a control group residing in quiet neighborhoods [92]. There is also some scientific evidence that children exposed to sources of intense noise are more likely to experience impairments in reading and language, especially in the case of pre-existing difficulties.

Considering all this evidence, the World Health Organization Parma Declaration demanded that all the stakeholders get cooperatively involved in reducing the exposure of children to noise to protect them from its harmful effects [93]. The recommended threshold of WHO guidelines for noise level in school classrooms is 35 dB(A): this level should prevent disturbance of communication during class. Actually, it is very common that these noise limits are exceeded and noise intensity in schools can reach as much as 60–80 dB(A) in normal classes; during school workshops and in sport areas, the limit values for workplace can be exceeded [94].

It is also necessary to consider the complexity of the individual factors, involved in the onset of effects and symptoms; some of these seems to be individual sensitivity to noise or coping strategies. For example, from a study conducted on young women [95], it emerged that noise can cause a physiological reaction to stress when they are not effective or there are no suitable strategies to counteract it (for example, the disturbance caused by noise was less annoying for those who knew they could close the windows).

Even how leadership quality is assessed appears to mitigate the negative effects of occupational noise exposure [96], as exposed employees may feel that the problem is recognized and addressed by management; such reassurance could alleviate stress induced by noisy sources. Moreover, it cannot be excluded that some of these individual variables, such as subjective noise sensitivity, paranoia and sleep quality, can be used as positive predictors for the onset of chronic noise exposure impairments [97].

In recent years, as also found in our analysis, many authors are shifting the focus of their research on the neuro-physiological and biochemical alterations suffered by the nervous system and the auditory system, due to noise. In fact, from the data found also through our analysis, it can be hypothesized that noise can directly cause neurobehavioral alterations (through biochemical mechanisms) or indirectly (as a consequence of hearing loss or speech intelligibility or due to its distracting action). Some studies have shown how, with the same sound pressure level, the annoyance increases the more the high frequency content of the noise increases, because such high values interfere with verbal communications [98]. Furthermore, the increased effort of interpretation required to compensate for this discomfort causes tension and psychological fatigue in the exposed subjects, leading to unconscious behavioral modifications [99].

As for the biochemical hypotheses, some experimental studies have shown that noise exposure can cause structural damage to the cochlea and stimulate hyperactivity in the central auditory system, including the cochlear nucleus, inferior colliculus, and auditory cortex. Furthermore, non-classical hearing-sensitive brain areas can (e.g., the lateral amygdala and striatum) can be triggered by noise exposure, which directly activates the brain's emotion-fear system via the thalamus. In this way, noise can activate defense responses involving the mechanisms of the hypothalamus–pituitary–adrenal (HPA) axis. Long-lasting activation of the HPA axis can cause disturbances in hormonal balance as well as morphological and functional changes in the brain, which may be the potential mechanism for subsequent noise-induced cognitive impairment and neurobehavioral manifestations [100–103].

A strong element of this scientific work is that we have not found another systematic review that addresses this issue in the same way as we do. At the same time, another past systematic review would have given us the opportunity, updating the scientific literature, to compare ourselves with past works and highlight the differences or changes made in the approach to these issues. Other limitations of this review could be the wide variability of samples selected in the various studies, the wide diversity of categories examined, and sometimes a non-standardized and validated methodology regarding questionnaires administered to the exposed or scientific experiments. Additionally, some of the studies lack quantitative measurements and description of the characteristics of noise, thus making it difficult identifying the detrimental and annoying features of noise to plan targeted interventions. Eventually, confounding factors related to the possible extraprofessional noise exposure should be addressed. In fact, even though all the studies refer to occupational noise and its effects, we cannot exclude voluptuary noise exposure of the subjects involved in the studies. However, in all studies, the professional exposure results the main source of noise identified by the investigators, thus making it possible to relate it to the neurobehavioral effects described.

5. Conclusions

In conclusion, the issue is still widely debated and involves more and more aspects. A greater number of studies will be needed to bring new knowledge on this topic, both as regards the evidence of behavioral disorders and as regards the hormonal and biochemical knowledge underlying these alterations, in order to prevent inconvenience for residents in the areas most exposed and for all those workers who report such disturbances. New opportunities for intervention are desirable in the future, including increased public awareness, worker training programs and education, government intervention addressing health and safety concerns, promotion of regulation, and government funding to enforce higher safety measures, especially in some work sectors such as schools.

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Appendix A

Study	Risk of bias domains					Overall
	D1	D2	D3	D4	D5	
Abbasi	-	-	+	-	+	
Alimohammadi 2019	+	+	-	-	+	
Alimohammadi 2018	+	-	-	+	+	
Alimohammadi 2010	+	-	+	+	-	+
Azuma	-	-	-	+	+	
Burns	-	+	×	-	-	
Cheng	-	-	+	+	-	
Clausen	+	-	-	+	-	
Deng	×	+	-	-	-	×
Di Blasio	+	-	+	×	-	
Eysel-Gosepath	-	×	×	×	-	×
Friedriksson 2015	-	+	-	-	+	
Friedriksson 2019	+	-	+	×	-	
Freiberg	-	+	+	-	+	
Habibi	×	×	+	-	-	
Hansen	-	×	×	-	×	×
Horsten	-	+	+	-	-	
Hua	-	×	-	-	-	
Jahncke	-	-	×	×	×	×
Keller 2017	-	+	×	-	×	
Keller 2018	+	×	-	+	-	
Kim	+	+	-	-	×	
Kristiansen	×	+	+	-	-	
Mahendra Prashanth	-	×	-	+	-	
Mapuranga	+	×	-	-	+	
Milenkovic	-	-	×	-	-	
Molesworth	×	-	-	×	×	×
Monteiro	-	-	-	+	-	
Nari	+	-	+	+	+	+
Oenning	-	×	-	+	-	
Onchang	+	-	×	+	-	
Realyvásquez	×	-	-	×	-	
Schlittmeier	+	×	-	-	×	
Sjodin	+	-	×	-	-	
Sloof	-	×	×	-	+	
Smith	-	×	×	×	-	×
Tomic	-	-	-	×	×	×
Wassermann	+	-	-	-	-	
Wright	×	-	×	×	-	×
Yoon	×	-	-	+	+	
Yuen	+	-	+	-	×	

Domains:
D1: Bias arising from the randomization process.
D2: Bias due to deviations from intended intervention.
D3: Bias due to missing outcome data.
D4: Bias in measurement of the outcome.
D5: Bias in selection of the reported result.

Judgement
● High
● Some concerns
● Low
NA

Figure A1. Risk of bias summary.

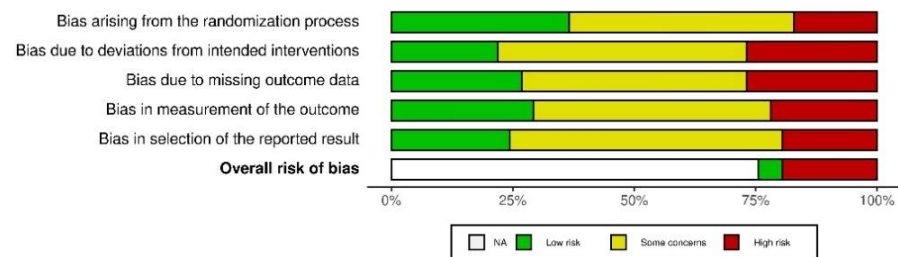


Figure A2. Risk of bias summary.

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