Applied Ergonomics 118 (2024) 104264

Contents lists available at ScienceDirect

Applied Ergonomics

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

Review article

The after-effects of occupational whole-body vibration on human cognitive, visual, and motor function: A systematic review

Barbara Halmai [a,*], Timothy P. Holsgrove [b], Samuel J. Vine [a], David J. Harris [a], Genevieve K.R. Williams [a]

[a] University of Exeter, Public Health and Sport Sciences, St Luke's Campus, Exeter, EX1 2LU, UK
[b] University of Exeter, Engineering Streatham Campus, Exeter, EX4 4PY, UK

ARTICLE INFO

Keywords:
Occupational
Vibration exposure
Human response
Safety

ABSTRACT

Whole-body vibration (WBV) is prevalent in labour-related activities and can have adverse effects on the health and performance of the individuals exposed. However, evidence regarding the extent to which human functionality is affected following occupational WBV exposure has not been collated. The current systematic review sought to synthesize existing literature and assess the strength and direction of evidence regarding the acute after-effects of occupational WBV exposure on cognition, visual function, postural stability, and motor control. We conducted a comprehensive search of AMED, CINAHL, MEDLINE, PubMED, Psychology and Behavioural Sciences Collection, SPORTDiscus, APA PsychInfo, Cochrane Library, EMBASE, HMIC, Global Health, ProQuest Central, Scopus, Web of Science, and the US National Technical Information Service on April 26, 2023. Studies that quantified vibration exposure and measured acute changes in cognition, visual function, postural stability, and motor control from baseline to post-vibration were considered without date restriction. Out of the 2663 studies identified, 32 were eligible for inclusion. Based on the Risk of Bias in Non-Randomized Studies of Exposure (ROBINS-E) tool, the studies demonstrated low (66%), moderate (25%) and high risk of bias (9%). The findings indicate that after exposure to WBV, postural stability either deteriorates or remains unchanged. Inconsistent effects of WBV on cognition were reported, while visual function and motor control showed no pronounced changes following WBV. This might be attributed to assessment limitations such as learning effects in neuropsychological and motor tasks, and non-functional measures of vision employed. There was a lack of consistency in the characterization of vibration exposure and the assessment of associated effects on functional performance. Current evidence is therefore insufficient to provide definitive guidance for updating occupational health and safety regulations regarding WBV. However, this review highlights the potential for WBV to jeopardize post-exposure human performance and, consequently, safety. The completion of the review was supported by a UKRI EPSRC training grant. The review has been registered on PROSPERO (ref CRD42023391075).

1. Introduction

The modern world encompasses a wide range of activities that expose humans to vibration. Whole-body vibration (WBV), characterized by mechanical oscillations transmitted to the human body through supporting surfaces (e.g., seat, backrest, standing platform) is prevalent in various industries such as transportation, military, construction, mining, forestry, and agriculture. Growing epidemiological evidence suggests various health complications resulting from occupational WBV exposure, some of which may be irreversible (Patterson et al., 2021). Commonly reported pathologies include chronic pain and musculoskeletal disorders around the spine, neck and shoulders (Boshuizen et al., 1990; Bovenzi and Hulshof, 1999; Bovenzi et al., 2017). In addition, an increased incidence of vascular and nervous diseases has also been reported among workers exposed to WBV (Krajnak, 2018). Recently, concerns have emerged about more transient effects and the transmission of vibration to the occupant's head, which may have repercussions for neurological and cerebral function.

The effects of vibration on the individuals exposed can manifest during, immediately after (referred to as acute after-effects), or after

---

* Corresponding author.
E-mail addresses: b.halmai@exeter.ac.uk (B. Halmai), t.holsgrove@exeter.ac.uk (T.P. Holsgrove), s.j.vine@exeter.ac.uk (S.J. Vine), d.j.harris@exeter.ac.uk (D.J. Harris), g.k.r.williams@exeter.ac.uk (G.K.R. Williams).

https://doi.org/10.1016/j.apergo.2024.104264
Received 18 October 2023; Received in revised form 25 January 2024; Accepted 3 March 2024

longer periods of repeated exposure (chronic effects). During vibration, deleterious alterations in physiological, psychological, neuromuscular, perceptual, and motor function have been reported consistently (Bhuiyan et al., 2022; Griffin and Lewis, 1978; Kjellberg, 1990; Lewis and Griffin, 1978; Nakashima, 2005; Savage et al., 2016; Von Gierke et al., 1991). Disruption to perceptual and motor performance during vibration are primarily due to mechanical interference (i.e., unintended movement of the arms and the eyes due to vibration) (Conway et al., 2007; Kjellberg, 1990), however, the mechanisms underlying cognitive performance degradation under vibration are unclear (Conway et al., 2007). The extent to which these effects persist after the cessation of vibration are also poorly understood, partially due to the limited number of studies and the paucity of synthesized evidence available (Mani et al., 2010; Savage et al., 2016). Thus, this review focuses on the acute after-effects of exposure to WBV on human functionality.

As optimal cognitive, perceptual, and motor function (i.e., movement-related functions such as postural stability and motor control in this review) are critical for overall safety, there is a need to further investigate the relationship between occupational vibration exposure and subsequent alterations in aspects of brain function. For example, perturbations in the perceptual-motor system can lead to a distorted perception of an individual's physical capabilities and the spatiotemporal constraints of the environment. This could potentially heighten the risk of accidents and injuries, particularly in vehicle operation, military or sports settings (Eagle et al., 2020). Even subtle alterations in the coupling between perception and action can present a life-threating risk in occupations such as the military or emergency services, where personnel frequently perform complex and hazardous tasks upon alighting from vibrating vehicles.

The degree to which performance and health is affected by WBV is influenced by the mechanical characteristics (e.g., frequency, magnitude, direction) and the duration of the exposure (Conway et al., 2007). It has been suggested that people are most vulnerable to vibration along the body's vertical axis (along the spinal column), in a frequency range of 1 Hz–20 Hz (Mansfield, 2004), whereas vibration in the fore-and-aft and lateral directions may be most detrimental at lower frequencies, in the range of 1–4 Hz (Griffin and Brett, 1997). However, occupational activities such as driving vehicles and operating heavy machinery generally expose occupants to multi-axial stochastic (i.e., non-deterministic) vibration, leading to the measured effects often being the result of combined vibration profiles. There is a range of different ways of quantifying vibration magnitude according to the characteristics of the exposure. For example, vibration magnitude is often expressed as the root means square (RMS) acceleration (a_{rms}), which describes the severity of vibration using an average over the measurement duration. The advantage of using the a_{rms} is that it allows different signals to be compared (e.g., low frequency, high amplitude vs. high frequency, low amplitude). Occupational WBV exposures are calculated (BS ISO 2631-1, 2011; EU Directive, 2002; Health and Safety Executive, 2005) by applying weightings to provide the frequency-weighted acceleration (a_w), which aims to account for the varying harmfulness of certain frequency ranges based on empirical data and biodynamic modelling. The a_w can be extrapolated to an 8-h reference period (A (8)), representative of exposure over a typical working day (BS ISO 2631-1, 2011). However, when vibration contains occasional shocks, the vibration dose value (VDV) is suggested to be more suitable. VDV is calculated using the acceleration time history to the fourth power, which provides an accumulative measure of vibration rather than a running average. To decide whether the A (8) or the VDV is more suitable to characterize the vibration exposure, a crest factor (CF) can be used. The CF is the modulus of the ratio between the peak and the mean of the frequency-weighted acceleration, and should the CF exceed a value of 9, the VDV is generally recommended over the A (8) value. International and European standards have been developed to assist controlling vibration exposure in occupational settings (BS ISO 2631-1, 2011; EU Directive, 2002; Health and Safety Executive, 2005), however, it is important to note that exposure action values (EAV) and exposure limit (ELV) values have been primarily designed to assess the risks related to musculoskeletal disorders, particularly those pertaining spinal health (BS ISO 2631-1, 2011; BS ISO 2631-5, 2018).

The aim of the current work was to systematically review existing literature on how exposure to occupational WBV acutely affects aspects of human functionality based on quantitative measures of vibration exposure and changes in cognition, visual function, postural stability, and motor control. In addition, the review aims to evaluate the direction and strength of evidence regarding the acute after-effects of occupational WBV exposure and the extent to which experimental evidence supports or opposes current guidelines in estimating the risks associated with occupational WBV exposure on human functioning.

2. Materials and methods

2.1. *Eligibility criteria*

We included quantitative, repeated-measures studies that examined the acute effects of occupational WBV on cognitive or visual function, postural stability, or motor control. We focused exclusively on studies that consisted of healthy adults (age ≥18 years). For evaluating health effects, we adhered to the recommendations of the International Organization for Standardization (BS ISO 2631-1, 2011) and considered vibration frequencies ranging from 0.5 Hz to 80 Hz. To be eligible for inclusion, studies were required to provide quantification of vibration exposure in the published paper, or supplementary documentation. We excluded studies that investigated hand-arm vibration, chronic exposure to occupational WBV, WBV used as a therapeutic or exercise tool, as well as transient WBV stimuli lasting ≤2 min that were employed to increase alertness. The primary outcomes under investigation were pre-to post-exposure changes in cognitive function, visual function, postural stability, and motor control. Studies using quantitative techniques were considered, while those employing qualitative assessment or relying solely on symptom report were excluded.

2.2. *Information sources and search strategy*

The concept of the systematic review was validated by a preliminary search across multiple platforms (PROSPERO, JBI, Google Scholar, MEDLINE), which returned no existing or ongoing reviews addressing the chosen topic. An initial search was conducted on MEDLINE (Ovid interface) and Web of Science to identify pertinent articles. Text words contained in the titles, abstracts, and keywords of relevant papers were used to develop a full search strategy (available at https://osf.io/vcft5) (Aromataris and Munn, 2020). Search terms were identified in five major areas: (1) WBV; (2) cognition; (3) vision; (4) postural stability; and (5) motor control. The following databases were searched: AMED (EBSCOhost), CINAHL (EBSCOhost), Psychology and Behavioural Sciences Collection (EBSCOhost), SPORTDiscus (EBSCOhost), APA PsychInfo (Ovid), Cochrane Library (Ovid), EMBASE (Ovid), HMIC (Ovid), Global Health (Ovid), MEDLINE (Ovid), PubMED, ProQuest Central (Health and Medical Collection, Science and Technology Collection), Scopus, Web of Science, and the US National Technical Information Service. The search strategy was adapted to fit each database. Studies needed to be published in English, with no restriction on the year of publication. Beyond primary research articles, other sources of information were also considered such as peer-reviewed manuscripts, conference proceedings, technical reports, and theses. An additional 'snowball' search was conducted on all eligible sources that underwent full-text screening to identify relevant studies not returned during database search (Park et al., 2021).

2.3. *Selection process*

The study selection process was in accordance with guidelines developed by Tawfik et al. (2019). Following the database search, all identified sources of evidence were gathered and imported into EndNote 20 (Clarivate, UK). Duplicates were removed automatically with a manual follow-up. The screening procedure was executed independently by two researchers. Titles and abstracts were assessed against the eligibility criteria and relevant articles were retrieved in full. During the full-text screening phase, reasons for exclusion were recorded and reported. In instances where disagreements arose between reviewers, resolution was reached through discussion or with an additional reviewer.

2.4. Quality assessment

Quality assessment was conducted using the Risk of Bias in Non-Randomized Studies of Exposure (ROBINS-E) tool (Higgins et al., 2023). The tool uses signalling questions to assess the risk of bias across seven domains (confounding factors, measurement of exposure, participant selection, post-exposure intervention, missing data, measurement of outcomes, and selection of reported results) to facilitate informed decision-making regarding the quality of each relevant study. Questions in each domain have response options such as ‘Yes’, ‘Probably yes’, ‘Probably no’, ‘No’ and ‘No information’, generating a suggested judgement (i.e., low, some, high or very high risk of bias with regards to the domain) based on the answers. Final decisions were made considering the risks of bias arising from all domains.

2.5. Data extraction and synthesis

The research team developed a data extraction tool (available at https://osf.io/hgu4q), which was used to extract information regarding the study population, context, outcomes, methodologies, vibration measurement, and findings relevant to the review question. Data extraction was carried out by a single reviewer, and subsequently checked, reconciled, and discussed with the other two reviewers. If information on vibration characteristics or performance outcomes were insufficient in recent papers (published in 2010 or later), efforts were made to contact corresponding authors via email to request additional data.

The synthesis and presentation of data followed the SWiM framework (Campbell et al., 2020) and the Cochrane Handbook (Higgins et al., 2022b). Sources of evidence were grouped by study outcomes: (1) cognitive function, (2) vision, (3) postural stability, and (4) motor control. All further syntheses were conducted according to these domains. Given the heterogeneity of reported vibration exposures and outcomes, a vote counting method was adopted. Results were presented in harvest plots, based on the direction of exposure effects (Higgins et al., 2022; Thomson and Thomas, 2013). The criteria for categorizing these effects were developed as follows:

- Beneficial or harmful:
    - ○ if any of the outcome variables were statistically significant ($p < 0.05$) and there was no evidence of effect in the opposite direction.
- No change
    - ○ if vibration had no effect on the outcomes and all variables were statistically not significant.
- Uncertain
    - ○ if the direction of change was mixed or not clear.
    - ○ if significance values were not available.

3. Results

3.1. Database search results

The systematic search of 14 databases and 1 register returned 1,430 articles after removing duplicates, and 8 additional studies were identified via citation searching. A total of 1,398 articles did not meet our criteria or could not be retrieved, leaving 32 studies to be included in the current review (Fig. 1). Of the 4 authors contacted during the screening process, 2 authors provided us with additional information necessary for inclusion.

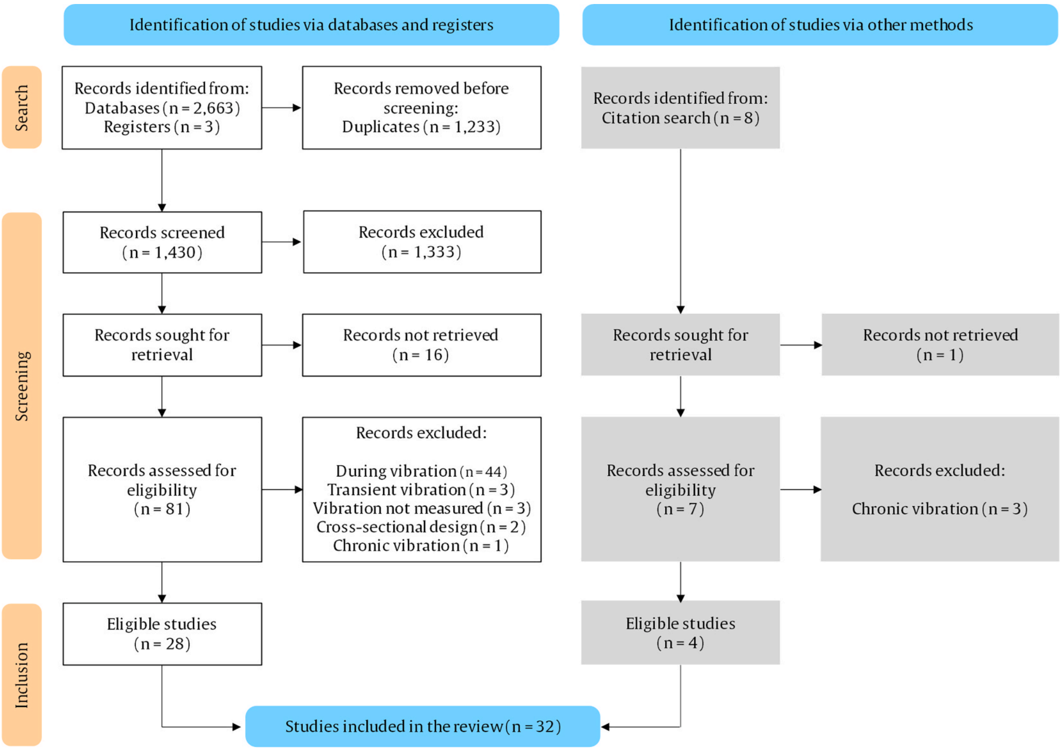

Fig. 1. PRISMA flow chart for the study selection process (Haddaway et al., 2022).

3.2. Risk of bias assessment

All 32 studies included in the current review are deemed appropriate based on the ROBINS-E Risk of Bias tool. Studies demonstrated low risk of bias ($n_s = 21$, 66%), some concerns ($n_s = 8$, 25%), and high risk of bias ($n_s = 3$, 9%). Detailed results of the risk of bias assessment are presented in Table 1.

3.3. Study characteristics

The reviewed studies were published between July 1960 and April 2023 (Fig. 2). A total of 461 participants were involved, with 89% of them being male ($n_p = 412$). The mean age of the participants ranged from 20 to 55 years across studies, representative of the working population. Only 56% of the studies ($n_s = 18$) had an adequate control condition or group (i.e., no vibration).

3.4. Measurement and characteristics of vibration

Quantification of vibration varied substantially across studies. The duration of the exposure was reported throughout, which was accompanied by a single or a combination of two or more metrics of vibration (Fig. 3). WBV was generated using laboratory-based vibration platforms or equipment during field use ($n_s = 27$, 84%; $n_s = 5$, 16%, respectively). Measurement locations included the floor, the seat, and the head, however, 40% of the studies ($n_s = 13$) only reported vibration metrics that were used as an input for the vibration platform, and not the vibration at the contact point or elsewhere on the participants (i.e., on the head).

There were 114 different vibration exposure levels (referred to as exposure trials) investigated across 32 studies (data available at https://osf.io/mtdb2). Participants were exposed to vibration in either a seated or a standing posture ($n_t = 105$ trials, 92% and $n_t = 9$ trials, 8%, respectively). Two main occupational domains were identified: *On-road transportation* trials ($n_t = 49$ trials, 43%) focused on the effects of vehicular WBV, induced by or simulating trucks and automobiles on paved surfaces, and the majority of trials were characterized by sinusoidal vibration applied in a single axis (horizontal or vertical). *Heavy equipment, off-road, air and maritime transportation* trials ($n_t = 21$ trials, 18%) focused on the human response to exposures such as those encountered in vehicles and machinery relating to forestry, agriculture, mining, military and aviation industries. Although there were large differences across trials, more than half of them comprised stochastic, multi-axial vibration exposure. There were also trials whose occupational relevance was *not specified* ($n_t = 44$ trials, 39%). In these trials, participants were primarily exposed to sinusoidal vibration in the vertical axis.

3.5. Effects of occupational WBV on human function

3.5.1. Cognitive function

In total, 52 trials from 11 studies focused on cognitive changes as a function of acute WBV exposure (Fig. 4A). A variety of tools have been used to assess aspects of cognitive function, including the Psychomotor Vigilance Task (PVT), search and memory (SAM) test, psychomotor measures, forward and backward recall, random number generation, and attention tests.

There were 38 trials (from 5 studies) representative of vibration during *on-road transportation*, of which 19 exposure trials (59%) resulted in significant worsening of cognitive function. These impairments included increases in reaction time (Azizan and Fadhilah, 2020; Du et al., 2018; Hornick et al., 1961) and the number of attention lapses (Azizan and Fadhilah, 2020) following various WBV exposures. In fewer cases, choice reaction time following fore-and-aft vibration (Hornick et al., 1961) and psychomotor vigilance following vertical vibration exposure (Wang, 2021) was maintained. Improved logical thinking was observed following a 22-min simulated ride on public transport vehicles of different intensities (Firmino et al., 2021), however, these results should be treated with caution due to the high risk of study bias (Table 1).

The effects of vibration associated with the operation of *heavy equipment, off-road, air and maritime vehicles* on mental performance were investigated in 9 trials (from 4 studies). Only one exposure trial reported significant deterioration of psychomotor vigilance after a simulated all-terrain vehicle ride above the ELV (Yung et al., 2018). In contrast, PVT performance was maintained when vibration levels were kept below the ELV (Yung et al., 2017, 2018). Intermittent shock exposure associated with high-speed boat travel (McMorris et al., 2009) and simulated all-terrain vehicle travel (Yung et al., 2018) generally did not induce acute changes in cognitive function. However, when suspension seats were utilized during maritime travel, performance on the backward number recall test improved from pre-to post-exposure, though no pre-post changes in cognitive function were reported when using fixed seats (McMorris et al., 2009). Short-duration vibration exposure (8 min) representing naval ships and aircrafts did not affect cognitive performance (Guignard et al., 1981).

Five trials (from 2 studies) in the cognitive domain did not link their chosen vibration exposure levels to industry. Harmful effects of high frequency stochastic vibration exposure (1–30 Hz, 20 min) on psychomotor function could not be verified in a population of mature workers (Kowalski and Zając, 2017). Improved reaction time performance has been found following sinusoidal vibration of similar duration, however, this was due to a learning effect (Marelli et al., 2022).

3.5.2. Visual function

To date, there is no evidence of transient visual impairment following WBV exposure. Evidence from 46 trials (4 studies) demonstrated unaffected near and far visual acuity (Desrosiers, 1988), flicker fusion rate (Guignard et al., 1976) and saccadic function (Yung et al., 2018) after occupational vibration exposure (Fig. 4B). An enlargement of the visual field (up to $+2^\circ$) has been recorded after transverse vibration associated with simulated ground vehicle travel, however, this subtle improvement may be due to practice (Hornick et al., 1961). A significant decrease in blink frequency rate has also been noted after low-intensity vibration representative of all-terrain vehicle travel, which indicates reduced levels of alertness (Yung et al., 2018).

3.5.3. Postural stability

Nineteen research studies focused on acute changes in postural stability after exposure to occupational WBV exposure, with 82 different vibration levels (trials) investigated across 21 studies (Fig. 4C). All studies incorporated a bipedal upright stance in their postural stability assessment, while more challenging tasks (e.g., unipedal stance or dynamic balance exercise) were rarely included as assessment tools. There was a lack of consistency in test duration and sightedness (i.e., eyes open vs. closed), but most outcome metrics reflecting the subjects' balancing ability were derived from centre of pressure (COP) data.

There were 38 trials (from 5 studies) that simulated on-road driving conditions, of which 6 trials (16%) induced negative changes in postural control, with significant increases in COP displacement in the anterior-posterior (Aghamiri et al., 2022; Halverson, 2013) and medial-lateral (Aghamiri et al., 2022) directions, total path length (Halverson, 2013; Tatsuno and Maeda, 2023), sway velocity (Park et al., 2021) and area (Park et al., 2021; Tatsuno and Maeda, 2023) measured immediately after vibration exposure. When postural stability was assessed for prolonged periods (5-min assessment) (Kjellberg and Wikstrom, 1987) or long after cessation of vibration (15 min) (Hornick et al., 1961), no significant changes in COP metrics were present ($n_t = 32$, 82%).

The postural effects of vibration associated with the operation of heavy equipment, off-road, air and maritime vehicles were tested in 17 different exposure trials (9 studies). Suboptimal postural control (7 trials, 41%) during static tasks was indicated by increased COP

Table 1
Risk of bias assessment based in the ROBINS-E tool.

Study	1*	2	3	4	5	6	7	R
Aghamiri et al. (2022)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Azizan and Fadhilah (2020)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Azizan et al. (2017)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Bastek et al. (1977)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Cornelius et al. (1994)	🟢	🟡	🟢	🟢	🟢	🟢	🟢	M
Desrosiers (1988)	🟢	🟡	🟢	🟢	🟢	🟢	🟢	M
Du et al. (2018)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Firmino et al. (2021)	🟢	🟢	🟡	🟢	🟢	🔴	🟡	H
Golhosseini et al. (2022)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Guignard et al. (1976)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Guignard et al. (1981)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Halverson (2013)	🟢	🟡	🟢	🟢	🟢	🟡	🟢	H
Hornick et al. (1961)	🟢	🟢	🟢	🟢	🟢	🟡	🟢	M
Kjellberg and Wikstrom (1987)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Kowalski and Zając (2017)	🟢	🟢	🟢	🟢	🟢	🟢	🟡	M
Landstrom et al. (1988)	🟢	🟡	🟢	🟢	🟢	🟢	🟢	M
Lu et al. (2019)	🟢	🟡	🟢	🟢	🟢	🟡	🟢	H
Mani et al. (2015)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Manninen (1988)	🟢	🟢	🟢	🟢	🟢	🟡	🟢	M
Manninen and Ekblom (1984)	🟢	🟢	🟢	🟢	🟢	🟡	🟢	M
Marelli et al. (2022)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Martin et al. (1980)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
McKay (1972)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
McMorris et al. (2009)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Park et al. (2021)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Pollard et al. (2017)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Santos et al. (2008)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Seidel et al. (1980)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Tatsuno and Maeda (2023)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Wang (2021)	🟢	🟡	🟢	🟢	🟢	🟢	🟢	M
Yung et al. (2017)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L
Yung et al. (2018)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	L

*Risk of bias arising from: confounding factors (Domain 1), measurement of exposure (Domain 2), participant selection (Domain 3), post-exposure intervention (Domain 4), missing data (Domain 5), measurement of outcome (Domain 6), reported results (Domain 7). Overall ratings (R) are low (L), moderate (M) and high (H) risk of bias.

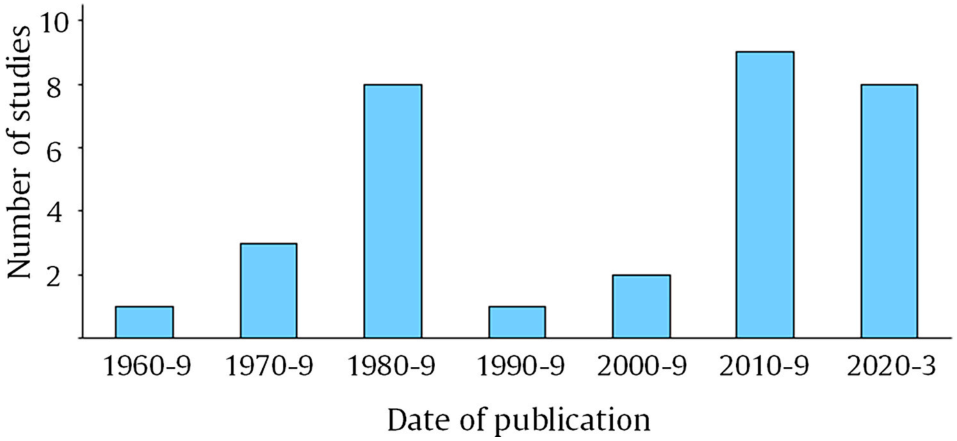

Fig. 2. Distribution of studies by publication date.

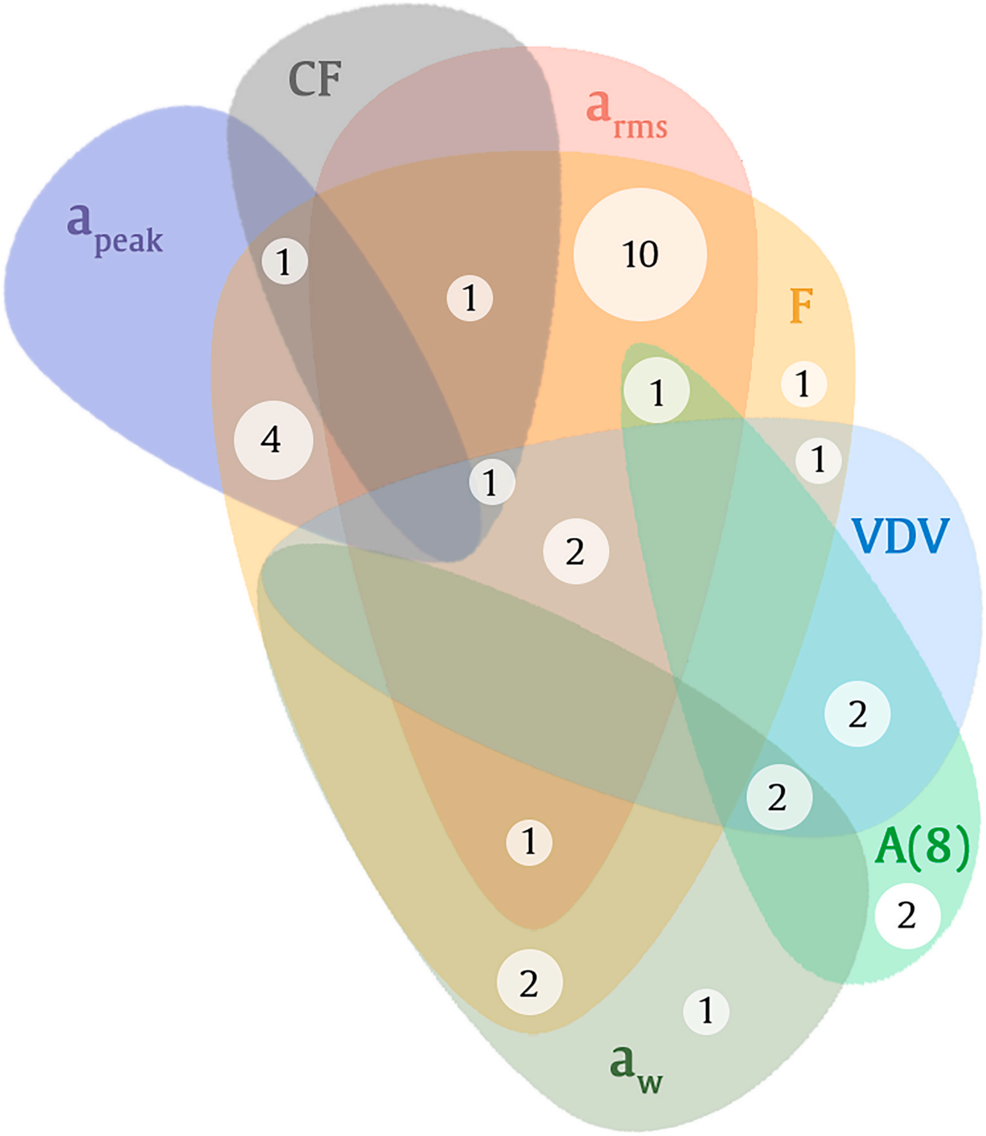

Fig. 3. Venn diagram illustrating the overlap (or the lack thereof) of vibration metrics reported across studies. Bubbles represent the number of studies in each category: a_{rms} = root means square acceleration; F = frequency; VDV = vibration dose value; A (8) = frequency-weighted acceleration with respect to an 8 h reference period; a_w = frequency-weighted acceleration; a_{peak} = peak acceleration; CF = crest factor.

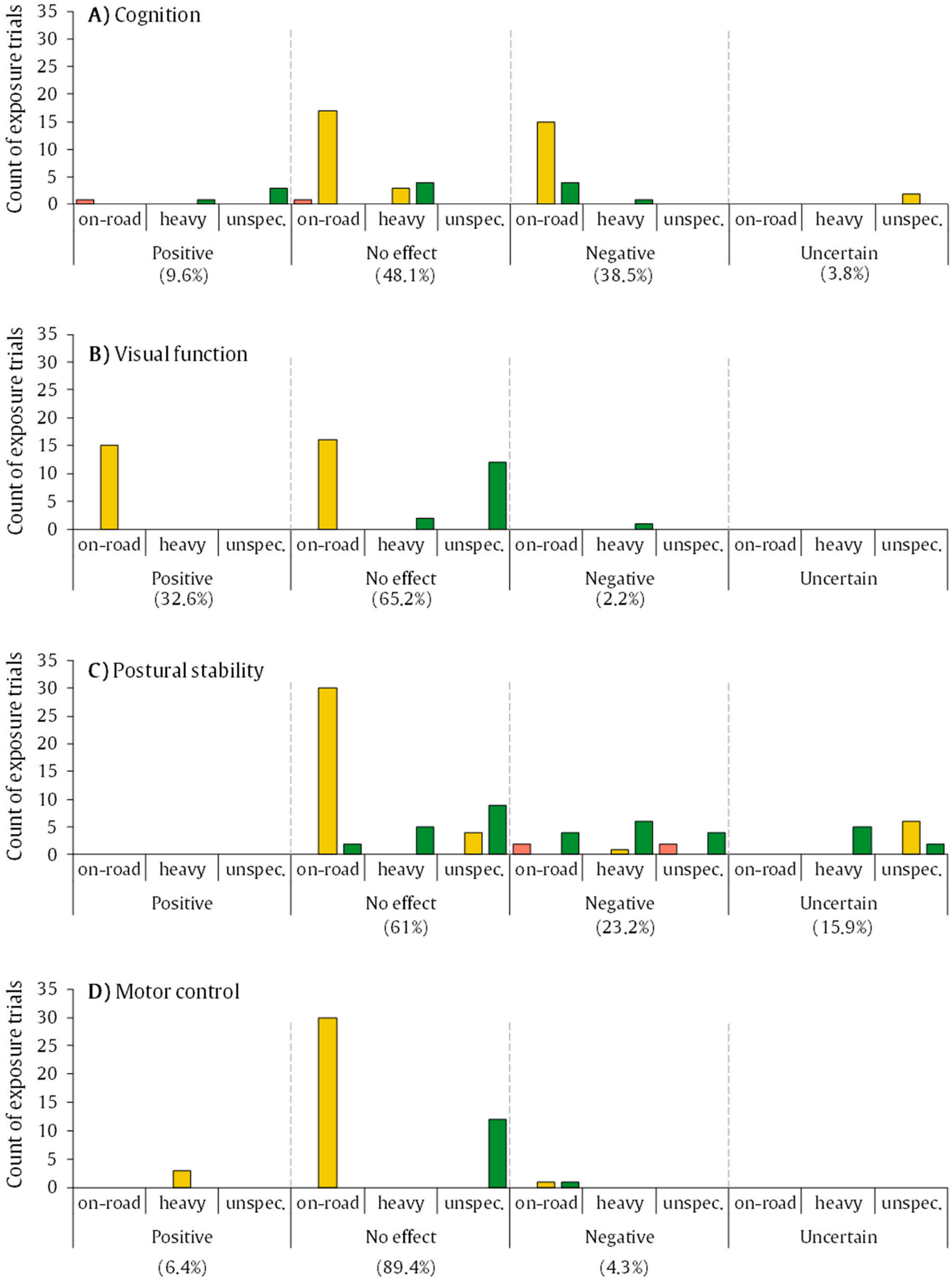

Fig. 4. Harvest plots illustrating the acute after-effects of occupational whole-body vibration on cognition (**A**), visual function (**B**), postural stability (**C**) and motor control (**D**). The *x* axis depicts the direction of the effects observed. The height of the bars (*y* axis) reflects the number of exposure trials from all studies in each setting (*on-road* = exposures representing paved land transportation; *heavy* = exposures representing off-road, maritime and air transportation as well as operation of heavy machinery; *unspec.* = unspecified occupational exposure trials). The colour of the bars corresponds to the risk of bias category (red = high; yellow = moderate; green = low). Data available from https://osf.io/2ymvt. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

displacement in the anterior-posterior (Golhosseini et al., 2022; Park et al., 2021; Yung et al., 2018) and medial-lateral (Golhosseini et al., 2022; Park et al., 2021) direction, sway velocity (Mani et al., 2015; Park et al., 2021) and area (Park et al., 2021). Limits of stability during dynamic balance tasks were not affected by WBV exposure (Mani et al., 2015; Park et al., 2021), however, enlargement of COP displacement and sway area was found during heavy object lifting (Mani et al., 2015). Although the direct comparison of vibration effects was hindered by inconsistent quantification of exposures, there was a tendency towards maintained postural stability after lower intensity vibration associated with mining (Cornelius et al., 1994; Pollard et al., 2017; Santos et al., 2008) and farming operations (Yung et al., 2017, 2018), regardless of the presence of shocks. On the other hand, aircraft-induced vibration elicited alterations in postural stability, indicated by changes in sway power spectral density (McKay, 1972) and increases in postural force amplitude (Martin et al., 1980; McKay, 1972).

Twenty-seven trials *of unspecified occupational* vibration (from 7 studies) demonstrated variable effects on postural stability, including 7 trials reporting degradation (26%). Significant impairments in postural stability were only measured after a vertical, low frequency exposure (2 Hz, Bastek et al., 1977). Higher frequencies (3–11 Hz) elicited no observable changes in linear measures of postural stability (Bastek et al., 1977; Manninen, 1988), while more complex measures, such as spectral composition, have revealed some changes (Manninen and Ekblom, 1984; Seidel et al., 1980). Similarly, a seated trial on side-alternating vibration plates operating at 20 Hz and 40 Hz induced detrimental changes in sensory integration required for maintaining balance, measured using the sensory organization test (Lu et al., 2019).

3.5.4. *Motor control*

Evidence from 47 trials (5 studies) suggests that aspects of motor control might be affected following occupational WBV exposure (Fig. 4D). Of all *on-road* vehicular vibration exposure trials ($n_t = 32$), only 6% (2 trials) resulted in manual control degradation, represented by the subjects' impaired steering ability when following a predetermined driving path (Azizan et al., 2017; Hornick et al., 1961). Although a similar trend was observed by Hornick et al. (1961), the results of the investigation did not reach significance. Lower limb movement control (i.e., regulation of driving speed via a foot pedal) is generally maintained following vehicular vibration exposure (Azizan et al., 2017; Hornick et al., 1961). In *maritime and air travel* ($n_t = 3$) and *unspecified occupational* trials ($n_t = 12$) manual dexterity was maintained regardless of the duration and frequency of the vibration (Desrosiers, 1988; Guignard et al., 1976). Some improvements in marker tapping tasks have been reported after short exposures, however, this has been attributed to learning effects (Guignard et al., 1981).

4. Discussion

The aim of the current review was to systematically map existing literature on the acute effects of exposure to occupational WBV on human functionality based on quantitative measures of vibration and changes in cognition, vision, postural stability, or motor control. Studies that quantified vibration exposure and subsequent changes in human performance were included and evaluated using a vote counting approach. In total, the results from 114 exposure trials from 32 studies were synthesized. Following exposure, measured changes in cognition (52 trials from 11 studies), visual function (46 trials from 4 studies), postural stability (82 trials from 21 studies), and motor control (47 trials from 5 studies) were reported. The interconnection between the investigated domains across studies is depicted in Fig. 5. The majority of analysed studies demonstrated a low risk of bias ($n_s = 21$, 65.6%), while the quality of the remaining studies was concerning ($n_s = 8$, 25%, moderate risk; $n_s = 3$, 9.4%, high risk of bias). Methodologies used to measure and characterize vibration exposure as well as subsequent effects on human performance exhibited substantial heterogeneity. Therefore, comparison between the findings of studies and evaluation of the combined strength of the evidence were impeded. Furthermore, discrepancies in the reported effects of WBV were identified, even in cases where vibration exposures and outcome assessments were similar.

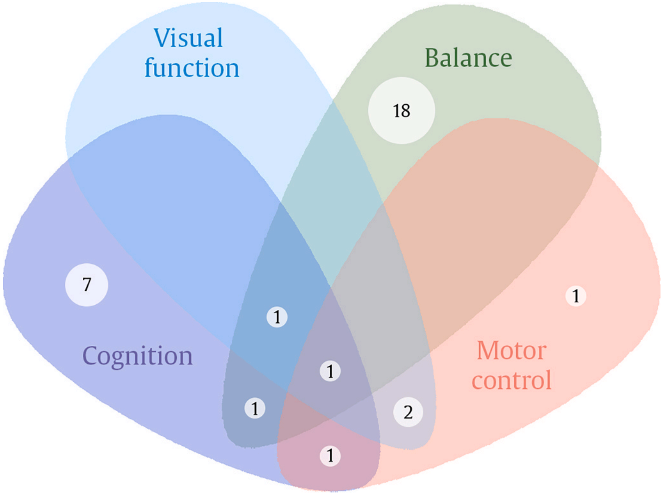

Fig. 5. Venn diagram illustrating the overlap of the four outcome domains. Bubbles represent the number of studies in each category.

We also aimed to assess the extent to which experimental evidence supports or opposes current guidelines in estimating the risks associated with occupational WBV exposure on human functioning. Vibration stress refers to the physical impact vibration has on the person exposed, characterized by factors such as frequency, magnitude, direction, and duration. Although the International Standards Organization guidelines for vibration measurement and evaluation (BS ISO 2631-1, 2011) are well-established, exposures were expressed inconsistently across studies (Fig. 3), and references to EAV and ELV were rarely stated. Consequently, it was not possible to estimate the influence of different vibration levels on the probability of cognitive, perceptual, or motor impairments following occupational WBV exposure. Of concern, some evidence suggests that exposures below established EAV might not be entirely safe from a musculoskeletal perspective (Bovenzi et al., 2017), nor concerning neuropsychological function (Azizan and Fadhilah, 2020; Du et al., 2018) and postural stability (Mani et al., 2015; Park et al., 2021; Tatsuno and Maeda, 2023; Yung et al., 2018). Therefore, it becomes imperative to expand the focus beyond musculoskeletal issues and recognize the impact of WBV exposure on neurological health. Development of innovative guidelines that encompass both musculoskeletal and neurological dimensions of vibration exposure would be valuable for enhancing the overall safety and well-being of workers.

Furthermore, reported vibration levels were predominantly derived from measurement devices placed on vibrating surfaces, thus it remains unclear how much vibration was experienced at different body parts, particularly at the head. Given that repetitive head motions can induce cerebral disruption (Bazarian et al., 2014; Laksari et al., 2015) and impairments in neurocognitive function and motor control (Daneshvar et al., 2023; Mainwaring et al., 2018; Woodall et al., 2023), the omission of head vibration assessment in much of the vibration literature, existing standards, and occupational guidelines is concerning. Therefore, establishing head vibration assessment protocols, novel metrics and thresholds that can accurately estimate the likelihood of adverse neurological outcomes are crucial areas for future research and safety standard development.

Findings of the review indicated a tendency towards performance degradation following exposure to higher magnitudes of vibration (Aghamiri et al., 2022; Golhosseini et al., 2022; Tatsuno and Maeda, 2023; Yung et al., 2018) or lower frequencies (Bastek et al., 1977). However, an interaction between vibration amplitude and frequency could not be verified from the papers reviewed (Guignard et al., 1976; Hornick et al., 1961). It appeared that multi-axial stochastic vibration has the greatest potential to elicit detrimental after-effects across all aspects of functionality (impairments reported in 67% of the trials), but no firm conclusions can be made for sinusoidal and single axis exposures due to variation in methodological approaches and unequivocal findings across studies. Exposure duration is a potential moderating factor of WBV effects: the longer vibration is present, the greater the potential for disrupted human response (Conway et al., 2007; Mansfield, 2004). Results from the current review suggest that the duration of the exposure alone does not necessarily equate to more pronounced changes in performance, but together with vibration magnitude, it might exert a synergistic effect. Previous propositions have highlighted the role of vibration stress in determining biodynamic, physiological and psychological responses (i.e., vibration strain) during exposure (Conway et al., 2007; Dupuis and Zerlett, 1986), yet the associations with post-exposure repercussions remain to be elucidated.

Studies have revealed inconsistent changes in cognitive function from baseline to post-exposure. It is important to acknowledge the challenges of neuropsychological testing when interpreting the findings. Factors such as the task design, administration and learning effects can influence results, necessitating caution when making inferences to WBV effects and potential health and safety implications. For example, difficulty of a task might moderate cognitive performance following WBV (McMorris et al., 2009), as overly simple and too complex tasks can both diminish the motivation to perform well (Atkinson, 1966). Improvements in post-exposure cognitive performance are sometimes attributed to learning effects (Guignard et al., 1981; Marelli et al., 2022), however, increased psychological arousal induced by WBV exposure can also elicit similar effects (i.e., Yerkes-Dodson Law). Theoretically, low vibration stress might be sufficient in eliciting optimal levels of arousal that persist after the cessation of vibration and allows for maximized cognitive performance (Fig. 6). However, degradation of cognitive function has also been found (e.g., Azizan and Fadhilah, 2020; Du et al., 2018; Hornick et al., 1961; Nakashima and Cheung, 2006), which might be due to the additional extraneous cognitive load (Sweller, 2010) associated with processing the sensory input (i.e., vibration), or reductions in brain blood flow associated with more severe vibrations (Kong et al., 2023). It must be noted that the time course of cognitive-cerebral restoration after vibration is unclear, therefore the timing of the performance assessments is crucial to evaluate the transiency of vibration effects. In addition, it is imperative to quantify different levels of vibration exposure at the level of the head in relation to beneficial and harmful after-effects on neuropsychological function.

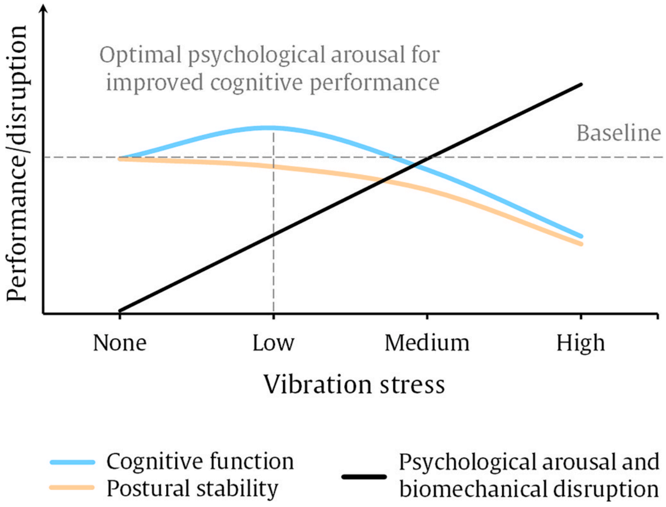

Fig. 6. Theoretical relationship between vibration stress and post-exposure cognitive performance and postural control. Theoretical changes are induced by increases in psychological arousal and biomechanical interference associated with vibration exposure. Low vibration stress might be sufficient in eliciting optimal levels of arousal and hence improved cognitive performance (i.e., Yerkes-Dodson law), while more severe vibration can disrupt cerebral physiology and potentially neural function. Vibration stimulation can overload the sensorimotor system, which results in transient disruption in postural stability following exposure. Evidence indicates that greater vibration stress may be associated with more pronounced degradation of postural stability.

Regarding motor function, the available evidence suggests that WBV yields a disruptive effect on tasks involving static postural stability, and manual dexterity to a lesser extent. While the potential influence of muscular fatigue (Adamo et al., 2002) and prolonged sitting (Kjellberg and Wikstrom, 1987) cannot be ruled out, it is proposed that alterations in postural stability and manual control might be related to proprioceptive perturbation induced by WBV. It has been suggested that mechanical vibration primarily stimulates Ia muscle spindle afferents (Burke et al., 1976; Roll et al., 1989), transmitting intensive and irrelevant sensory input to motor-related brain areas for processing (Duclos et al., 2007; Radovanovic et al., 2002). Consequently, it appears that vibration alters the frame of reference used for maintaining balance or moving the limbs, which lasts beyond vibration exposure (Duclos et al., 2007; Gilhodes et al., 1992). Suboptimal motor responses can therefore be expected after vibration until the proprioceptive systems is reset, which is assumed to take 15–20 min (Hornick et al., 1961; Wierzbicka et al., 1998). Martin et al. (1980) further supports the peripheral origin of balance disturbances following WBV, evidenced by the absence of increased postural sway after vibration applied directly to the head (i.e., cerebral or vestibular issues) as opposed to the leg. Future studies are warranted to uncover post-exposure balance strategies and the way WBV influences an individual's dependence on visual, vestibular and somatosensory feedback to maintain equilibrium using novel approaches such as multi-sensory perturbations (Caccese et al., 2020) and virtual reality-based dynamic sensory assessment (e.g., Chien et al., 2014; Wang et al., 2021).

In instances where postural adjustments were guided by visual feedback (i.e., eyes-open balancing tasks) following WBV, performance degradation was more pronounced than in eyes-closed conditions (Ahuja et al., 2005; Golhosseini et al., 2022; Halverson, 2013; Oullier et al., 2009). Degradation of visually guided motor performance in clinical populations have been partially attributed to deficits in eye movement control (Friedrich et al., 2008; Murray et al., 2014; Oldham et al., 2021; Verheij et al., 2012), though to date, there is no evidence indicating visual dysfunction following WBV exposure. This lack of evidence might be a consequence of gross measures of vision employed in previous investigations such as Snellen and Landolt C charts for visual acuity (Desrosiers, 1988; Guignard et al., 1976; Hornick et al., 1961). Gaze behaviour (i.e., the functional way people control their gaze) is likely to be more susceptible to alterations induced by vibration or injury, due to intricate neuromuscular mechanisms involved in gaze control. Metrics of oculomotor function are considered useful to indicate compromised neural integrity, cerebral dysfunction, and psycho-physiological states, particularly in high-risk industries (Heitger et al., 2002; Martinez-Marquez et al., 2021; Schweizer et al., 2023). Therefore, expanding the application of eye-tracking technologies to assess post-vibration oculomotor control and exploring its implications for human performance would be of considerable value. As impairments in cognitive function, visual perception, postural stability and motor control can potentially increase the risk of occupational accidents and musculoskeletal injury (Chang et al., 2016; Eagle et al., 2020; Herman et al., 2015; Jebelli et al., 2016; Martinez-Marquez et al., 2021), evaluating functional performance alterations associated with WBV exposure can provide an indirect means of improving worker safety.

5. Conclusions

The effects of WBV are a matter of concern for occupational ergonomists, safety specialists, and health practitioners. Vibration stress is strongly associated with musculoskeletal issues and reduced comfort, however, the way in which cognitive, perceptual, and motor function is affected following WBV has been less defined. This systematic review evaluated the current state of knowledge based on quantitative research studies, and proposed areas for future research. Post-exposure performance degradation was most pronounced in postural stability, particularly in eyes-open conditions. Findings on cognitive function were inconsistent; studies indicated maintained or degraded performance after WBV, and cases of beneficial after-effects have also been found. A limited number of studies demonstrated negligible after-effects of occupational vibration on motor control and visual function. The high variability in the characterization of vibration exposure across studies hinders the identification of vibration levels responsible for adverse consequences. Although the review implies that occupational vibration exposure could lead to transient disruption to cognitive and postural control even below exposure limit values, current evidence is insufficient to drive visionary actions to improve health and safety regulations concerning occupational WBV. Future research should prioritize the standardization of vibration measurement, with particular emphasis on assessing vibration at the contact point and at the head. Additionally, attention is required to identify a threshold level of vibration exposure that induces cognitive, visual, and motor deficits following WBV. Leveraging advanced technologies such as eye-tracking and ecologically valid performance assessments to capture neurological and behavioural alterations following whole-body and head vibration exposure would significantly advance our understanding.

Funding

The authors would like to acknowledge the UKRI EPSRC training grant (EP/W524451/1 #270416), which supported the completion of this research. For the purpose of open access, the author has applied a 'Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising from this submission.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apergo.2024.104264. Procedures and tools used during the completion of the review are made available on the Open Science Framework at https://doi.org/10.1016/j.apergo.2024.104264.

References

Adamo, D., Martin, B., Johnson, P., 2002. Vibration-induced muscle fatigue, a possible contribution to musculoskeletal injury. Eur. J. Appl. Physiol. 88 (1–2), 134–140. https://doi.org/10.1007/s00421-002-0660-y.

Aghamiri, S.Z., Aliabadi, M., Farhadian, M., Golmohammadi, R., Shafiee Motlagh, M., 2022. The simultaneous exposure to heat and whole-body vibration on some motor skill functions of city taxi drivers. Med. Lavoro 113 (5), e2022045. https://doi.org/10.23749/mdl.v113i5.13432.

Ahuja, S., Davis, J., Wade, L.R., 2005. Postural stability of commercial truck drivers. Impact of extended durations of whole-body vibration 49 (19), 1810–1814. https://doi.org/10.1037/e577482012-012.

Aromataris, E., Munn, Z., 2020. *JBI Manual for Evidence Synthesis*. Joanna Briggs Institute. https://doi.org/10.46658/JBIMES-20-01.

Atkinson, J.W., 1966. A Theory of Achievement Motivation. John Wiley & Sons.

Azizan, A., Fadhilah, M.S., 2020. Cognitive reaction time performance and subjective drowsiness: a critical evaluation of the effect of whole-body vibrations [Article]. Malaysian Journal of Public Health Medicine 20 (Specialissue1), 267–271. https://doi.org/10.37268/MJPHM/VOL.20/NO.SPECIAL1/ART.661.

Azizan, A., Fard, M., Azari, M.F., Jazar, R., 2017. Effects of vibration on occupant driving performance under simulated driving conditions. Appl. Ergon. 60, 348–355. https://doi.org/10.1016/j.apergo.2016.12.020.

Bastek, R., Buchholz, C., Denisov, E.I., Enderlein, G., Kramer, H., Malinskaja, N.N., Meister, A., Metz, A., Mucke, R., Rhein, A., Rothe, R., Seidel, H., Sroka, C., 1977. Comparison of the effects of sinusoidal and stochastic octave-band-wide vibrations - a multi-disciplinary study - Part I: experimental arrangement and physical aspects [Article]. Int. Arch. Occup. Environ. Health 39 (3), 143–152. https://doi.org/10.1007/BF00405659.

Bazarian, J.J., Zhu, T., Zhong, J., Janigro, D., Rozen, E., Roberts, A., Javien, H., Merchant-Borna, K., Abar, B., Blackman, E.G., 2014. Persistent, long-term cerebral white matter changes after sports-related repetitive head impacts. PLoS One 9 (4), e94734. https://doi.org/10.1371/journal.pone.0094734.

Bhuiyan, M.H.U., Fard, M., Robinson, S.R., 2022. Effects of whole-body vibration on driver drowsiness: a review. J. Saf. Res. https://doi.org/10.1016/j.jsr.2022.02.009.

Boshuizen, H.C., Bongers, P.M., Hulshof, C.T.J., 1990. Back disorders and occupational exposure to whole-body vibration. Int. J. Ind. Ergon. 6 (1), 55–59. https://doi.org/10.1016/0169-8141(90)90050-C.

Bovenzi, M., Hulshof, C.T.J., 1999. An updated review of epidemiologic studies on the relationship between exposure to whole-body vibration and low back pain (1986-1997). Int. Arch. Occup. Environ. Health 72 (6), 351–365. https://doi.org/10.1007/s004200050387.

Bovenzi, M., Schust, M., Mauro, M., 2017. An overview of low back pain and occupational exposures to whole-body vibration and mechanical shocks. Med. Lavoro 108 (6), 419–433. https://doi.org/10.23749/MDL.V108I6.6639.

British Standards Institution, 2011. ISO 2631 Mechanical vibration and shock — evaluation of human exposure to whole-body vibration. In: Part 1: General Requirements.

British Standards Institution, 2018. ISO 2631 Mechanical vibration and shock — evaluation of human exposure to whole-body vibration. In: Part 5: Method for Evaluation of Vibration Containing Multiple Shocks.

Burke, D., Hagbarth, K.E., Löfstedt, L., Walling, B.G., 1976. The responses of human muscle spindle endings to vibration of non-contracting muscles. J. Physiol. 261 (3).

Caccese, J.B., Santos, F.V., Yamaguchi, F., Jeka, J.J., 2020. Persistent Visual and Vestibular Impairments for Postural Control Following Concussion, vol. 95. https://doi.org/10.1212/01.wnl.0000720008.66446.5a.

Campbell, M., Mckenzie, J.E., Sowden, A., Katikireddi, S.V., Brennan, S.E., Ellis, S., Hartmann-Boyce, J., Ryan, R., Shepperd, S., Thomas, J., Welch, V., Thomson, H., 2020. Synthesis without meta-analysis (SWiM) in systematic reviews: reporting guideline. BMJ l6890. https://doi.org/10.1136/bmj.l6890.

Chang, W.-R., Leclercq, S., Lockhart, T.E., Haslam, R., 2016. State of science: occupational slips, trips and falls on the same level. Ergonomics 1–23. https://doi.org/10.1080/00140139.2016.1157214.

Chien, J.H., Eikema, D.-J.A., Mukherjee, M., Stergiou, N., 2014. Locomotor sensory organization test: a novel paradigm for the assessment of sensory contributions in gait. Ann. Biomed. Eng. 42 (12), 2512–2523. https://doi.org/10.1007/s10439-014-1112-7.

Conway, G.E., Szalma, J.L., Hancock, P.A., 2007. A quantitative meta-analytic examination of whole-body vibration effects on human performance. Ergonomics 50 (2), 228–245. https://doi.org/10.1080/00140130600980888.

Cornelius, K.M., Redfern, M.S., Steiner, L.J., 1994. Postural stability after whole-body vibration exposure [Article]. Int. J. Ind. Ergon. 13 (4), 343–351. https://doi.org/10.1016/0169-8141(94)90091-4.

Daneshvar, D.H., Nair, E.S., Baucom, Z.H., Rasch, A., Abdolmohammadi, B., Uretsky, M., Saltiel, N., Shah, A., Jarnagin, J., Baugh, C.M., Martin, B.M., Palmisano, J.N., Cherry, J.D., Alvarez, V.E., Huber, B.R., Weuve, J., Nowinski, C.J., Cantu, R.C., Zafonte, R.D., Mez, J., 2023. Leveraging football accelerometer data to quantify associations between repetitive head impacts and chronic traumatic encephalopathy in males. Nat. Commun. 14 (1) https://doi.org/10.1038/s41467-023-39183-0.

Desrosiers, J., 1988. The Measurement of Whole Body Vibration and its Effect on Load-Haul-Dump Operators in Underground Mining Simon Fraser University.

Du, B.B., Bigelow, P.L., Wells, R.P., Davies, H.W., Hall, P., Johnson, P.W., 2018. The impact of different seats and whole-body vibration exposures on truck driver vigilance and discomfort. Ergonomics 61 (4), 528–537. https://doi.org/10.1080/00140139.2017.1372638.

Duclos, C., Roll, R., Kavounoudias, A., Roll, J.P., 2007. Cerebral correlates of the "Kohnstamm phenomenon": an fMRI study. Neuroimage 34 (2). https://doi.org/10.1016/j.neuroimage.2006.06.050.

Dupuis, H., Zerlett, G., 1986. The Effects of Whole-Body Vibration. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-71245-6.

Eagle, S.R., Kontos, A.P., Pepping, G.-J., Johnson, C.D., Sinnott, A., Lagoy, A., Connaboy, C., 2020. Increased risk of musculoskeletal injury following sport-related concussion: a perception–action coupling approach. Sports Med. 50 (1), 15–23. https://doi.org/10.1007/s40279-019-01144-3.

EU Directive, 2002. Directive 2002/44/EC of the European Parliament and of the Council of 25 June 2002 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration) (sixteenth individual Directive within the meaning of Article 16 (1) of Directive 89/391/EEC): official Journal of the European Communities. L 117/13, 6.7.2002. The European Parliament and The Council of the European Union.

Firmino, S.G., Duarte, M.L.M., Neves, J.A.B., Viana, P.A.X., de Araújo, F.S.B., 2021. Whole body vibration influence on bus fare collectors evaluated by using a brain training mobile app. Int. Arch. Occup. Environ. Health 94 (3), 495–501. https://doi.org/10.1007/s00420-020-01601-x.

Friedrich, M., Grein, H.-J., Wicher, C., Schuetze, J., Mueller, A., Lauenroth, A., Hottenrott, K., Schwesig, R., 2008. Influence of pathologic and simulated visual dysfunctions on the postural system. Exp. Brain Res. 186 (2), 305–314. https://doi.org/10.1007/s00221-007-1233-4.

Gilhodes, J.C., Gurfinkel, V.S., Roll, J.P., 1992. Role of ia muscle spindle afferents in post-contraction and post-vibration motor effect genesis. Neurosci. Lett. 3 (2).

Golhosseini, S.M.J., Aliabadi, M., Golmohammadi, R., Farhadian, M., Akbari, M., Nahrani, M.H., Samavati, M., 2022. Combined effects of exposure to noise and vibration on human postural equilibrium under simulated driving conditions. Sound Vib. 56 (1), 37–49. https://doi.org/10.32604/sv.2022.014616.

Griffin, M.J., Brett, M.W., 1997. Effects of fore-and-aft, lateral and vertical whole-body vibration on a head-positioning task. Aviat Space Environ. Med. 68 (12), 1115–1122.

Griffin, M.J., Lewis, C.H., 1978. A review of the effects of vibration on visual acuity and continuous manual control, part I: visual acuity. J. Sound Vib. 56 (3), 383–413. https://doi.org/10.1016/S0022-460X(78)80155-2 [Review].

Guignard, J.C., Bittner, A.C., Carter, R.C., 1981. Methodological investigation of vibration effects on performance of three tasks. Proceedings of the Human Factors Society Annual Meeting 25 (1), 342–346. https://doi.org/10.1177/107118138102500190.

Guignard, J.C., Landrum, G.J., Reardon, E., 1976. Experimental Evaluation of International Standard (ISO 2631-1974) for Whole-Body Vibration Exposures. N.T.T. Servce. N. T. I. Service.

Haddaway, N.R., Page, M.J., Pritchard, C.C., McGuinness, L.A., 2022. PRISMA2020: an R package and Shiny app for producing PRISMA 2020-compliant flow diagrams, with interactivity for optimised digital transparency and Open Synthesis. Campbell Systematic Reviews 18 (2), e1230. https://doi.org/10.1002/cl2.1230.

Halverson, M., 2013. Evaluating Whole Body Vibration and Standing Balance Among Truck Drivers (Publication Number 1551041) [Master's, University of Washington]. ProQuest Dissertations & Theses Global, United States – Washington. https://www.proquest.com/docview/1497022414?accountid=10792.

Health and Safety Executive, 2005. Whole-body vibration. In: The Control of Vibration at Work Regulations.

Heitger, M.H., Anderson, T.J., Jones, R.D., 2002. Saccade sequences as markers for cerebral dysfunction following mild closed head injury. In: The Brain's Eye: Neurobiological and Clinical Aspects of Oculomotor Research. Elsevier, pp. 433–448. https://doi.org/10.1016/s0079-6123(02)40067-2.

Herman, D.C., Zaremski, J.L., Vincent, H.K., Vincent, K.R., 2015. Effect of neurocognition and concussion on musculoskeletal injury risk. Curr. Sports Med. Rep. 14 (3), 194–199. https://doi.org/10.1249/JSR.0000000000000157.

Higgins, J., Morgan, R., Rooney, A., Taylor, K., Thayer, K., Silva, R., Lemeris, C., Akl, A., Arroyave, W., Bateson, T., Berkman, N., Demers, P., Forastiere, F., Glenn, B., Hróbjartsson, A., Kirrane, E., LaKind, J., Luben, T., Lunn, R., Sterne, J., 2023. Risk of Bias in Non-randomized Studies - of Exposure (ROBINS-E).

Higgins, J., Thomas, J., Chandler, J., Cumpston, M.T.L., Page, M.J., Welch, V.A., 2022. Cochrane Handbook for systematic reviews of interventions. Cochrane, 6.3 ed. www.training.cochrane.org/handbook.

Hornick, R.J., Boettcher, C.A., Simons, A.K., 1961. The Effect of Low Frequency, High Amplitude, Whole Body, Longitudinal and Transverse Vibration upon Human Performance.

Jebelli, H., Ahn, D.R., Stentz, T.L., 2016. Fall risk analysis of construction workers using inertial measurement units: validating the usefulness of the postural stability metrics in construction. Saf. Sci. 84 https://doi.org/10.1016/j.ssci.2015.12.012.

Kjellberg, A., 1990. Psychological aspects of occupational vibration. Scand. J. Work. Environ. Health 16, 39–43, 1990.

Kjellberg, A., Wikstrom, B.O., 1987. Acute effects of whole-body vibration. Stabilography and electrogastrography. Scand. J. Work. Environ. Health 13 (3), 243–246. https://doi.org/10.5271/sjweh.2057.

Kong, L., Qiu, S., Chen, Y., He, Z., Huang, P., He, Q., Zhang, R., Feng, X., Deng, L., Li, Y., Yan, F., Yang, G., Feng, Y., 2023. Assessment of vibration modulated regional cerebral blood flow with MRI. Neuroimage 269. https://doi.org/10.1016/j.neuroimage.2023.119934.

Kowalski, P., Zając, J., 2017. Influence of vertical and horizontal whole-body vibration on some psychomotor and cognitive functions of employees age 50+ (pilot study). Journal of Vibroengineering 19 (3), 2174–2179. https://doi.org/10.21595/jve.2017.17834.

Krajnak, K., 2018. Health effects associated with occupational exposure to hand-arm or whole body vibration. J. Toxicol. Environ. Health, Part A B 21 (5), 320–334. https://doi.org/10.1080/10937404.2018.1557576.

Laksari, K., Wu, L.C., Kurt, M., Kuo, C., Camarillo, D.C., 2015. Resonance of human brain under head acceleration. J. R. Soc. Interface 12 (108), 20150331. https://doi.org/10.1098/rsif.2015.0331.

Lewis, C.H., Griffin, M.J., 1978. A review of the effects of vibration on visual acuity and continuous manual control, part II: continuous manual control. J. Sound Vib. 56 (3), 415–457. https://doi.org/10.1016/S0022-460X(78)80156-4 [Review].

Lu, S.-Y., Liu, C.-C., Lee, C.-L., Lin, Y.-H., 2019. Vertical vibration frequency and sitting posture effects on muscular loads and body balance. Int. J. Ind. Ergon. 74, 1. https://doi.org/10.1016/j.ergon.2019.102860.

Mainwaring, L., Ferdinand Pennock, K.M., Mylabathula, S., Alavie, B.Z., 2018. Subconcussive head impacts in sport: a systematic review of the evidence. Int. J. Psychophysiol. 132, 39–54. https://doi.org/10.1016/J.IJPSYCHO.2018.01.007.

Mani, R., Milosavljevic, S., Ribeiro, D.C., Sullivan, S.J., 2015. Effects of agricultural quad bike driving on postural control during static, dynamic and functional tasks - a field study. Int. J. Ind. Ergon. 50, 158–169. https://doi.org/10.1016/j.ergon.2015.08.007.

Mani, R., Milosavljevic, S., Sullivan, S.J., 2010. The effect of occupational whole-body vibration on standing balance: a systematic review. Int. J. Ind. Ergon. 40 (6), 698–709. https://doi.org/10.1016/j.ergon.2010.05.009.

Manninen, O., 1988. Changes in hearing, cardiovascular functions, haemodynamics, upright body sway, urinary catecholamines and their correlates after prolonged successive exposures to complex environmental conditions [Article]. Int. Arch. Occup. Environ. Health 60 (4), 249–272. https://doi.org/10.1007/BF00378472.

Manninen, O., Ekblom, A., 1984. Single and joint actions of noise and sinusoidal whole body vibration on TTS2 values and low frequency upright posture sway in men [Article]. Int. Arch. Occup. Environ. Health 54 (1), 1–17. https://doi.org/10.1007/BF00378724.

Mansfield, N.J., 2004. HUMAN RESPONSE TO VIBRATION, first ed. CRC Press.

Marelli, S., Ferrario, C., Lorenzini, G., Ravi, S.Y., Mazzoleni, A., Marchetti, E., Tarabini, M., 2022. Effects of the whole-body vibration direction on the cognitive response of standing subjects. Ergonomics 1–30. https://doi.org/10.1080/00140139.2022.2144647.

Martin, B., Gauthier, G.M., Roll, J.P., Hugon, M., Harlay, F., 1980. Effects of whole-body vibrations on standing posture in man. Aviat Space Environ. Med. 51 (8), 778–787.

Martinez-Marquez, D., Pingali, S., Panuwatwanich, K., Stewart, R.A., Mohamed, S., 2021. Application of eye tracking Technology in aviation, maritime, and construction industries: a systematic review. Sensors 21 (13), 4289. https://doi.org/10.3390/s21134289.

McKay, J.R., 1972. *A Study of the Effects of Whole-Body A(z) Vibration on Postural Sway* (AMRL-TR-71-121). N. T. I. Service.

McMorris, T., Myers, S., Dobbins, T., Hall, B., Dyson, R., 2009. Seating type and cognitive performance after 3 hours travel by high-speed boat in sea states 2-3. Aviat Space Environ. Med. 80 (1), 24–28. https://doi.org/10.3357/ASEM.2405.2009.

Murray, N., Salvatore, A., Powell, D., Reed-Jones, R., 2014. Reliability and validity evidence of multiple balance assessments in athletes with a concussion. J. Athletic Training 49 (4), 540–549. https://doi.org/10.4085/1062-6050-49.3.32.

Nakashima, A., 2005. *Whole-Body Vibration in Military Vehicles: A Literature Review* (Canadian Acoustics, Issue. D. R. a. D. Canada.

Nakashima, A., Cheung, B., 2006. The Effects of Vibration Frequencies on Physical, Perceptual and Cognitive Performance. Defence Research and Development.

Oldham, J.R., Mr, W., Howell, D.R., 2021. Impaired eye tracking is associated with symptom severity but not dynamic postural control in adolescents following concussion. J. Sport Health Sci. 10 (2) https://doi.org/10.1016/j.jshs.2020.10.007.

Oullier, O., Kavounoudias, A., Duclos, C., Albert, F., Roll, J.-p., Roll, R., 2009. Countering postural posteffects following prolonged exposure to whole-body vibration: a sensorimotor treatment. Eur. J. Appl. Physiol. 105 (2), 235–245. https://doi.org/10.1007/s00421-008-0894-4.

Park, J.-H., Kia, K., Srinivasan, D., Kim, J.H., 2021. Postural Balance Effects from Exposure to Multi-Axial Whole-Body Vibration in Mining Vehicle Operation, vol. 91. Applied Ergonomics. https://doi.org/10.1016/j.apergo.2020.103307. N.PAG-N.PAG.

Patterson, F., Miralami, R., Tansey, K.E., Prabhu, R.K., Priddy, L.B., 2021. Deleterious effects of whole-body vibration on the spine: a review of in vivo, ex vivo, and in vitro models. Animal Models and Experimental Medicine 4 (2), 77–86. https://doi.org/10.1002/ame2.12163.

Pollard, J., Porter, W., Mayton, A., Xu, X., Weston, E., 2017. The effect of vibration exposure during haul truck operation on grip strength, touch sensation, and balance. Int. J. Ind. Ergon. 57, 23–31. https://doi.org/10.1016/j.ergon.2016.11.009.

Radovanovic, S., Korotkov, A., Ljubisavljevic, M., Lyskov, E., Thunberg, J., Kataeva, G., Danko, S., Roudas, M., Pakhomov, S., Medvedev, S., Johansson, H., 2002. Comparison of brain activity during different types of proprioceptive inputs: a positron emission tomography study. Exp. Brain Res. 143 (3), 276–285. https://doi.org/10.1007/s00221-001-0994-4.

Roll, J.P., Vedel, J.P., Ribot, E., 1989. Alteration of proprioceptive messages induced by tendon vibration in man: a microneurographic study. Exp. Brain Res. 76 (1) https://doi.org/10.1007/bf00253639.

Santos, B.R., Lariviere, C., Delisle, A., Plamondon, A., Boileau, P.E., Imbeau, D., 2008. A laboratory study to quantify the biomechanical responses to whole-body vibration: the influence on balance, reflex response, muscular activity and fatigue. Int. J. Ind. Ergon. 38 (7–8), 626–639. https://doi.org/10.1016/j.ergon.2008.01.015.

Savage, R., Billing, D., Furnell, A., Netto, K., Aisbett, B., 2016. Whole-body vibration and occupational physical performance: a review. Int. Arch. Occup. Environ. Health 89 (2), 181–197. https://doi.org/10.1007/s00420-015-1062-x.

Schweizer, T., Wyss, T., Gilgen-Ammann, R., 2023. Detecting soldiers' fatigue using eye-tracking glasses: practical field applications and research opportunities. Mil. Med. 187, 11–12. https://doi.org/10.1093/milmed/usab509.

Seidel, H., Bastek, R., Brauer, D., Buchholz, C., Meister, A., Metz, A.M., Rothe, R., 1980. On human response to prolonged repeated whole-body vibration [Sensory Perception 2320]. Ergonomics 23 (3), 191–211. https://doi.org/10.1080/00140138008924734.

Sweller, J., 2010. Element interactivity and intrinsic, extraneous, and germane cognitive load. Educ. Psychol. Rev. 22 (2), 123–138. https://doi.org/10.1007/s10648-010-9128-5.

Tatsuno, J., Maeda, S., 2023. Effect of whole-body vibration exposure in vehicles on static standing balance after riding. Vibrations 6 (2), 343–358. https://doi.org/10.3390/vibration6020021.

Tawfik, G.M., Dila, K.A.S., Mohamed, M.Y.F., Tam, D.N.H., Kien, N.D., Ahmed, A.M., Huy, N.T., 2019. A step by step guide for conducting a systematic review and meta-analysis with simulation data. Trop. Med. Health 47 (1).

Thomson, H.J., Thomas, S., 2013. The effect direction plot: visual display of non-standardised effects across multiple outcome domains. Res. Synth. Methods 4 (1), 95–101. https://doi.org/10.1002/jrsm.1060.

Verheij, S., Muilwijk, D., Pel, J.J.M., van der Cammen, Mattace-Raso, F., van der Steen, J., 2012. Visuomotor impairment in early-stage alzheimer's disease: changes in relative timing of eye and hand movements. J. Alzheimer's Dis. 30 (1) https://doi.org/10.3233/JAD-2012-111883. IOS Press [Text].

Von Gierke, H.E., McCloskey, K., Albery, W.B., 1991. Military performance in sustained acceleration and vibration environments [Working Conditions & Industrial Safety 3670. Handbook of Military Psychology, pp. 335–364.

Wang, F., 2021. Evaluating the Effects of Altering Whole-Body Vibration Exposures on Truck Drivers' Vigilance (Publication Number 28722590) [Ph.D., University of Washington]. ProQuest Dissertations & Theses Global, United States – Washington.

Wang, Z., Lubetzky, A., Perlin, K., 2021. Walking balance assessment with eye-tracking and spatial data visualization. ACM SIGGRAPH 2021 Immersive Pavilion 1–2, 2021-08-05, 10.

Wierzbicka, M.M., Gilhodes, J.C., Roll, J.P., 1998. Vibration-induced postural posteffects. J. Neurophysiol. 79 (1) https://doi.org/10.1152/jn.1998.79.1.143.

Woodall, J., Sak, J., Cowdrick, K., Bove Muñoz, B.M., Jessica Trimpe, G., Mei, Y., Milton, H., Myhre, R., Rains, J., Hutchinson, C., 2023. Repetitive low-level blast exposure and neurocognitive effects in army ranger mortarmen. Mil. Med. 188 (3–4) https://doi.org/10.1093/milmed/usab394.

Yung, M., Lang, A.E., Stobart, J., Kociolek, A.M., Milosavljevic, S., Trask, C., 2017. The combined fatigue effects of sequential exposure to seated whole body vibration and physical, mental, or concurrent work demands. PLoS One 12 (12). https://doi.org/10.1371/journal.pone.0188468.

Yung, M., Tennant, L.M., Milosavljevic, S., Trask, C., 2018. The multisystem effects of simulated agricultural whole body vibration on acute sensorimotor, physical, and cognitive performance. Annals of Work Exposures & Health 62 (7), 884–898. https://doi.org/10.1093/annweh/wxy043.