Psychological effects of combined noise and whole-body vibration: a review and avenues for future research

J K Ljungberg[1,2*] and **F B R Parmentier**[3,4]
[1]Department of Human Work Sciences, Division of Engineering Psychology, Luleå University of Technology, Luleå, Sweden
[2]School of Psychology, Cardiff University, Cardiff, UK
[3]Department of Psychology, University of the Balearic Islands, Palma, Mallorca, Spain
[4]School of Psychology, University of Western Australia, Crawley, Western Australia, Australia

The manuscript was received on 16 July 2009 and was accepted after revision for publication on 24 February 2010.

DOI: 10.1243/09544070JAUTO1315

Abstract: Vehicle drivers are often exposed to noise, whole-body vibration (WBV), and mental loads, but the knowledge of how combined effects from multiple environmental stressors affect mental load and performance is sparse. Studies have shown that the effect of both vibration and noise combined can differ from those of either vibration or noise alone. For example, negative combined effects have been found on some cognitive tasks and impact on subjective ratings (e.g. annoyance and stress). Some of the studies investigating the combined effects of noise and WBVs suffer from low ecological validity, and few have investigated potential effects on cognitive functions. This sharply contrasts with the plethora of studies investigating the effect of noise on performance. It is argued that a potentially promising way to develop further research on combined effects of noise and WBV may be to adopt experimental methods and tasks that proved useful to understand the effect of sound exposure on performance (e.g. serial recall tasks) or of noise after-effects.

Keywords: cognition, performance, noise, vibration, whole-body vibration, subjective ratings, memory

1 INTRODUCTION

Professional vehicle drivers are often exposed to multiple stressors such as noise, vibration, and mental loads. In a complex driving situation, operators (e.g. drivers of heavy vehicles) sometimes have to manipulate two or more tasks at the same time in otherwise difficult work conditions, such as poor visibility due to bad weather conditions, the constant groan from the vehicle for hours, and the propagation of whole-body vibration (WBV) through their tired bodies. Yet, their ability to make appropriate decisions quickly is key to their efficiency, with all the safety and financial ramifications that this involves. Indeed, professional drivers such as those working in the forestry industry are also required to operate around the clock to be profitable and to provide a return on the expensive investments made in vehicles. The multiple sources of stress at play in such working environments may have a negative impact on the drivers' performance. For example, some aspects of the driving situation require focused attention from the operator, or the ability to switch between tasks while simultaneously holding information in their memories. The driver's mental load can be substantial and, combined with the exposure to noise and vibration, may impair the driver's performance, thereby increasing the risk of injury or accidents.

The physical effects of vibration are well documented, have been extensively studied, and form the basis of the international standards for noise and WBV that set acceptable occupational exposure levels [**1**, **2**]. In contrast, the body of literature examining the effects of the exposure to vibration on cognitive performance (including performance in tasks measuring, for example, different memory

**Corresponding author: Department of Work and Science, Division of Engineering Psychology, Luleå University of Technology, Luleå SE-971 87, Sweden.*
email: jessica.korning-ljungberg@ltu.se

processes but also attention, problem solving, and decision making) is rather meagre, especially with respect to exposures to WBV only (see, for example, reference [**3**]). The studies investigating the combined effects of noise and vibration on cognitive performance are rarer still (see, for example, references [**4**] and [**5**]), despite the fact that work environments involving one factor often include the other. The regulations and standards that govern how to conduct health risk assessments for both noise and vibration environments do not consider any possible combined or interactive effects between these two factors [**6–10**]. The issue of combined exposure is one that should command interest, however, for a misinterpretation of the possible interaction between the two factors may lead to the miscalculation of the risks or load faced by a driver.

The key aim of this review is to summarize the past research on the topic of combined noise and WBV, focusing on their psychological effects (the effects on cognitive performance and subjective experience). The focus of this review is on the psychological outcomes of WBV and its combination with noise. Therefore, studies were selected that used cognitive tasks or subjective ratings of psychological outcomes (e.g. annoyance, stress, and difficulty), administered during or after exposure to WBV, either in isolation or combined with noise. Given the paucity of such studies, distinguishing between application areas or types of specific physical stimulus would not be meaningful. Finally, the focus on the psychological effect of WBV also excluded the more frequent studies examining its general health effects, such as studies on low back pain, on neck issues, or on evaluating perceptual outcomes (see, for example, references [**11**] to [**13**]).

A subsidiary aim of this review was to highlight well-known methods and concepts from past research on the effect of the noise and sound on cognitive performance in order to suggest possible avenues for further research in the field of combined noise and WBV.

2 THE PSYCHOLOGICAL EFFECTS OF VIBRATION EXPOSURE

Most people are exposed to WBV when sitting, standing, or lying down on a vibrating surface. Vibration is mostly described and defined as follows; vibration can be transmitted through surfaces and can affect all parts of the body. WBV is most common when operating vehicles, with vibration travelling from the vibrating surface, for example, to the seat and footrest, all the way to the head, resulting in vibration of the latter. Exposure to WBV can affect negatively the operator's perceived comfort, perception, and health, depending on the physical characteristics of the vibration and the situation, such as their amplitude, exposure time, and body posture [**14**].

Because of the technical difficulty to reproduce realistic vibration in controlled environments, most empirical studies on WBV conducted in laboratory settings have exposed participants to WBV in only one direction, either up and down (see, for example, reference [**15**]), or fore and aft and also lateral (see, for example, reference [**16**]). In recent years, however, more advanced techniques have been developed to expose people to more realistic WBV while allowing the simultaneous measurement of their behaviours in a range of laboratory tests. Such simulations allow movements in all directions and thereby increase the ecological validity of laboratory studies. For example, Ljungberg and Neely [**4**, **5**] reproduced realistic WBV based on the vibration measured on a harvester (a heavy vehicle used in the forestry industry to cut logs) by using a six-degrees-of-freedom hydraulic motion platform (Rexroth HSE-6-MS-8-L-3D) on which the seat from a forest vehicle was mounted. Thumb-operated hand-held response buttons were fitted to collect responses from the participants in a series of cognitive tests. Visual stimuli were presented ahead of the participant using a projection screen, and loudspeakers were used to reproduce vehicle noises.

Kjellberg [**17**] concluded some years ago that empirical studies focusing on the psychological effects of WBV have mostly been focusing on their effects on visual perception and motor control tasks. The focal point in those studies has been on the effects of WBV exposure on mechanical interference (e.g. on the operation of joysticks during exposure), or the impact of WBV of various frequencies on visual acuity. Kjellberg also pointed out the lack of knowledge about the potential impact of WBV on cognitive processes, and the need to conduct further research in this area in order to gain a better understanding of the effects of WBV. A similar conclusion was drawn by Conway *et al.* [**18**] in a meta-analysis of past studies on vibration.

Rating scales have constituted the most common method to measure the subjective experience yielded by WBV. Based on the results gathered using such methodology, Kjellberg [**17**] concluded that doubling the vibration acceleration over a broad range of frequencies leads to nearly a doubling in subjective intensity and discomfort, and that subjective discomfort increases with increasing exposure time. This relationship was examined more closely in a case-control study by Abbate *et al.* [**19**]. Long-term effects caused by WBV on emotions were measured in forklift truck drivers with an average length of service of around 20 years by using a profile-of-mood-states questionnaire. Results showed that prolonged exposures to WBV yielded negative outcomes, such as fatigue–inertia, depression–dejection, and tension–anxiety.

Most studies also generally concur that an individual's subjective sensitivity to vibration depends mostly on the frequency of the vibration and is independent of acceleration levels, a conclusion also specified in the standard ISO 2631-1:1997 [**1**]. The guidelines suggest that a person is most sensitive to vibrations in the frequency span 4–8 Hz in the vertical direction *Z*, and in the span 1–2 Hz in the fore-and-aft direction *X* and lateral direction *Y*.

Other studies using subjective methods have focused on personality traits and their role in mediating the impact of WBV. Studies of this sort are sparse but their results indicate that personality traits should be considered when studying the cognitive effects of WBV. For example, Webb *et al.* [**20**] studied the role of the internal or external locus of control of individuals on their sensitivity to the effects of WBV exposure in a controlled laboratory study. The study used vibration levels similar to those typically obtained in cross-country vehicles, with an exposure time of 10 min. People with an internal locus of control are assumed to have a more active personality and to give themselves more credit for their performance, while people with an external locus of control tend to exhibit the opposite characteristics. The latter tend to believe that circumstances around them are not under their control and have therefore a more passive personality type. The results from the study by Webb *et al.* showed that personality type might have a moderating role on performance during exposure to WBV. Indeed, during exposure to WBV, participants with an internal locus of control performed significantly better in a motor-tracking task than did participants with an external locus of control. Another personality trait examined in the context of WBV studies is sensation seeking. A person with a high sensation-seeking (HSS) personality generally exhibits a higher need for novel, varied, complex, and intense experiences and emotional reactions compared with people with a low sensation-seeking (LSS) personality. Neely *et al.* [**21**], using a 6 Hz WBV (a frequency known from ISO 2631-1:1997 [**1**] to create a feeling of discomfort), showed that individuals with a HSS personality tend to expose themselves to WBV for durations twice as long (maximum exposure time, 2 min in that study), and at higher intensities than individuals with a LSS personality.

As mentioned earlier, studies investigating performance effects of WBV are rather sparse. Some field studies used objective psychological measurement methods, however. For example, Griffin and Hayward [**16**] conducted a controlled laboratory study where participants were reading while being exposed to 56 different types of WBV (similar to those obtained in underground trains) on two axes for durations of 30 s each. Their results showed that both fore-and-aft WBV and lateral WBV interfered with the subjective estimation of reading performance and reading speed. Furthermore, they found that with fore-and-aft vibration, their participants' reading speed was most impaired for a vibration frequency of 4 Hz with surrounding frequencies of vibration magnitudes between 1.0 m/s^2 and 1.25 m/s^2. The lateral vibration showed a similar effect, although to a lesser degree. Participants also tended to overestimate the decrement in their reading speed, suggesting that WBV increased their subjective judgement of task difficulty. More complex mental processes have also been investigated by the same research group. Sherwood and Griffin [**22**] used a 16 Hz sinusoidal vertical WBV of vibration magnitude 2.0 m/s^2 (comparable with those obtained in, for example, helicopters) to study their effects on learning. Compared with a control group the WBV group showed a decrease in an associative learning task (measuring the ability to encode, maintain, and recall new arbitrary associations between stimuli). In another study, Sherwood and Griffin [**3**] used a similar vibration stimulus but with vibration magnitudes of 0 m/s^2, 1.0 m/s^2, 1.6 m/s^2, and 2.5 m/s^2 to investigate the effects of WBV after an exposure of 30 min on performance in a short-term memory task. Surprisingly, the number of errors in that task only increased when participants were exposed to low-level vibrations (1.0 m/s^2), and no support was found for the hypothesis that a rising vibration magnitude generates a greater decrement in cognitive performance. These workers concluded that the relationship between WBV characteristics and cognitive functioning must therefore be more complex than a simple linear relationship between vibration magnitude and performance decrement in cognitive tasks. The reliability of these findings is questioned by the failure to replicate these effects, however. Indeed, Ljungberg *et al.* [**15**], using the same vibration exposure and cognitive task, found no effect of WBV on short-term memory after exposure for 20 min in each of four conditions (static, WBV, noise, and noise and WBV in combination). It is therefore unclear whether WBV does or does not impact on cognitive functions such as short-term memory. It is likely that other mediating factors, uncontrolled in these studies, may have affected the results, an issue highlighting the need for further systematic research in this field. Some tasks used to study performance may be more sensitive than others, possibly those requiring sustained attention. For example, Newell and Mansfield [**23**] used a choice reaction time task to study performance during exposure to a WBV stimuli (chosen to match those typically found in tracked off-road vehicles with dominant frequencies around the 2–8 Hz range) and different body postures, with or without an armrest. The results showed that WBV exposure affected reaction time negatively, especially when the body posture was twisted and the participants had no armrest.

The potential enduring effects of WBV on performance have also been the object of some work. More specifically, some research has investigated the susceptibility of participants to after-effects (i.e. effects occurring once vibration has stopped) caused by WBV on selective attention. For example, Ljungberg and Neely [**5**] reported degraded performance in a search-and-memory task in participants who, beforehand, had been exposed to WBV for approximately 44 min (combined with noise or not). Interestingly, no after-effect was found following exposure to noise only. Environmental stimuli (noise and WBV) typically encountered in heavy vehicles were applied in this experiment. During exposure, participants conducted cognitive tasks that required a high mental load, and subjective ratings of alertness were collected during and after exposure. A similar study (using the same environmental stimuli and same exposure time) was conducted by Ljungberg [**24**] but without the high mental load tasks during exposure, measuring only attention performance after exposure to WBV. No degraded performance was obtained in the latter, leading Ljungberg to conclude that the after-effects observed in the study by Ljungberg and Neely arose because the combination of a high mental load and WBV caused a lasting state of fatigue. Intriguingly, despite their degraded performance, participants in the study by Ljungberg and Neely reported higher alertness levels after the exposure to WBV than the levels measured after exposure to vehicle noise or to a control condition in which no vibration or noise was presented. This finding contrasts with the higher level of alertness obtained by Ljungberg [**24**] in a control condition compared with a WBV condition. Ljungberg concluded that this apparent discrepancy may result from differences between the experimental designs of the studies and that the higher task demands in the study by Ljungberg and Neely may have stressed participants more and thereby increased their alertness. To summarize, an overview of the findings obtained from studies examining the psychological outcomes of WBV suggests that an individual's subjective sensitivity to vibrations depends largely on the frequency more than the acceleration level, of the vibrations [**1**, **17**]. Furthermore, personality features seem to play a mediating role in the impact of WBV on behavioural outcomes [**20**, **21**], and prolonged exposure to WBV may also affect emotions negatively [**19**]. In studies measuring task performance directly, WBV exposure has shown to have an impact on certain cognitive functions as measured by short-term memory tasks and associative learning tasks [**3**, **22**]. WBV also appears to have negative effects on attention in the period of time following an exposure to WBV [**5**], but only when this exposure coincides with high-mental-load tasks [**24**]. Overall, however, systematic studies of the impact of WBV on behaviour and cognitive functions are too meagre to allow firm conclusions and more research is therefore needed.

3 COMBINED EFFECTS OF NOISE AND WHOLE-BODY VIBRATION

WBV is often experienced in noisy environments, so that field studies examining either of these factors in isolation may potentially miss their possible interactive effects. Yet few studies have been devoted to the measurement of combined effects on performance in cognitive tasks (see Table 1 for an overview), and many of those available in the literature date back to the 1970s.

The results from early studies are divergent and the effects of combined noise and WBV on cognitive performance seem to depend heavily on the specific intensity levels and frequencies of the noise and WBV. For example, some studies using a battery of cognitive tasks (e.g. mental arithmetic and choice reaction time task) found that, although a noise of 100–105 dB(A) presented together with a 5 Hz vibration (0.30 peak *g*) with a duration of 35 min resulted in fewer adverse effects on a motor tracking task

Table 1 Overview of studies measuring performance in cognitive tasks (combined or not with subjective rating scales) in studies combining noise and WBV. The table lists, for each study, the type of stimuli used, the nature of the cognitive task and rating measurement carried out, the main results, as well as an indication of the decrement in performance due to vibration, noise, or their combination

Reference	Stimuli	Cognitive task	Subjective ratings	Results	Changes in performance or ratings in vibration (V), noise (N), and combined (C) conditions
Grether *et al.* [**25**]	Broadband noise level at 100–105 dB(A) + 5 Hz WBV (0.30 peak *g*)	Tracking task Reaction time task Voice communication Mental arithmetic Visual acuity	—	Fewer adverse effects on horizontal and vertical tracking by combined exposure than by vibration alone	*Tracking task (horizontal), 29.3% (V) *Tracking task (vertical), 33.2% (V)
Grether *et al.* [**26**]	Broadband noise level at 100–105 dB(A) + 5 Hz WBV (0.30 peak *g*)	Tracking task Reaction time task Telephone test Mental arithmetic Visual acuity	—	Fewer adverse effects on horizontal and vertical tracking by combined exposure than by vibration alone. Longer reaction time in vibration condition	*Tracking task (horizontal), 18.3% (V) *Tracking task (vertical), 29% (V) *Reaction time task, 6% (V)
Harris and Shoenberger [**27**]	White-noise level at 65 100 dB(A) + complex 16 Hz WBV (0.36 m/s^2)	Complex counting task	—	Larger combined effects of noise and WBV when noise level was low	†Counting task, 11% (C)
Ljungberg *et al.* [**15**]	Recorded helicopter noise level at 77–86 dB(A) + 16 Hz WBV (*Z*) (1.0–2.5 m/s^2)	Short-term memory task	Ratings of intensity, difficulty, and annoyance	Higher ratings of difficulty and annoyance when noise and WBV were combined. No effect on performance	*Ratings of difficulty, 58.2% (C) *Ratings of annoyance, 67.8% (C)
Ljungberg and Neely [**4**] (experiment 2)	Recorded vehicle noise level at 78 dB(A) + 2–4 Hz WBV (1.1 m/s^2)	Logical reasoning task and a short-term memory task	Ratings of stress and difficulty	Highest ratings of stress in high-noise sensitive group when noise and WBV were combined. No effect on performance	*Ratings of stress, 51.4% (C)
Ljungberg and Neely [**5**]	Recorded vehicle noise level at 78 dB(A) + 2–4 Hz WBV (1.1 m/s^2)	Selective attention task	Ratings of alertness	Degraded performance after exposure to WBV. Increased ratings of alertness after WBV and decreased ratings of alertness after noise exposure	*Selective attention task, 15.6% (V) *Ratings of alertness, 12.5% (V), 12.9% (N)
Ljungberg [**24**]	Recorded vehicle noise level at 72 dB(A) + authentic vehicle WBV with dominant frequency 2–20 Hz (0.87 m/s^2)	Selective attention task	Ratings of alertness and annoyance	Decreased ratings of alertness after WBV exposure and highest ratings of annoyance after combination of WBV and noise. No performance effects	*Ratings of alertness, 18.2% (V) *Ratings of annoyance, 75.5% (C)
Sandover and Champion [**28**] (experiment 1)	Broadband noise level at 84.8 dB(A) + broadband (*Z*) WBV (1.18 m/s^2)	Arithmetic task	—	Decreased performance in single-stressor conditions	*Arithmetic task, 28.8% (V), 27.2% (N)
Sommer and Harris [**6**]	Noise level 60 dB(A) and 100 dB(A) + 6 Hz WBV (0.10g_z)	Tracking task	—	Vibration combined with 60 dB noise produced greater impairment in horizontal tracking than when combined with a noise stimulus played at 100 dB	†Tracking task, 24% (C, 60 dB noise), 3.2% (C, 100 dB noise)

*Relative to a control condition.
†Relative to a noise-only condition.

than vibration alone [**25**, **26**], a combination of noise (with a level rising from 100 dB(A) to 110dB(A)) with a 6 Hz (0.1 m/s^2 (Z)) vibration decreased performance compared with vibration presented in isolation [**6**]. Furthermore, Harris and Shoenberger [**27**], using a complex counting task showed that increasing the intensity of noise presented alongside WBV may not always worsen their effects on performance. In their study, a noise stimulus of 65 dB(A) combined with a complex sinusoidal vibration of 2.6 Hz, 4.1 Hz, 6.3 Hz, 10 Hz, and 16 Hz (0.36 m/s^2) with a duration of 30 min diminished performance further in the counting task than a 100 dB(A) noise exposure combined with the same vibration. Additionally, it was also found that both the single 100 dB(A) noise exposure and the single vibration exposure degraded performance in the counting task. Furthermore, Sandover and Champion [**28**] also used an arithmetic task but failed to find any combined effects of noise (broadband noise ranging up to 90dB(A)) and WBV (broadband vertical axis vibration presented at three levels: 0.59 m/s^2, 0.834 m/s^2, and 1.18 m/s^2). A decrement in performance was observed for noise and vibration presented in isolation (compared with a control condition with no sound or vibration), but only for high intensity levels (1.18 m/s^2 vibration and a mean noise level of 84.8 dB(A)). The results were, however, complicated by the finding that at lower intensities (0.83 m/s^2 vibration and mean noise level of 82 dB(A)), noise and vibration (presented in isolation) yielded an increase in performance.

The scarcity of such studies and the variability in their results make the interpretation of their findings difficult. Furthermore, the stimuli used suffer from low ecological validity (e.g. noise levels up to 110 dB(A) and WBV presented in one direction only), so that their results may not be generalizable to vehicle environments. On the other hand, these studies do highlight that certain motor and cognitive processes may be susceptible to environmental stressors such as noise and WBV presented as single stimuli as well as in combination.

More recent studies [**4**, **5**, **15**, **24**] investigated the combined effects of noise and WBV using a wider range of cognitive tasks and more realistic noise and vibration. In contrast with previous work, these studies reproduced the noise and vibration recorded in the field in the laboratory by using a programmable six-degrees-of-freedom hydraulic motion platform on which participants sat. Four conditions were compared, with participants being exposed to noise only, to WBV only, to both combined, or to a control condition (silence and no vibration). The battery of cognitive tasks included a logical reasoning task [**29**], a short-term memory task [**30**], and a search-and-memory task measuring selective attention. The noise and WBV exposures were recorded in or simulated from vehicle environments (forwarders and helicopters). Across these studies, no effect of noise, vibration, or their combined presentation was observed in any of the cognitive tasks. Interestingly, however, the combined exposure yielded greater subjective ratings of annoyance and difficulty [**15**], raising the issue of the relationship between these measures.

A few more studies have focused on the effects of combined noise and WBV on various subjective ratings. For example, Manninen [**31**] found higher subjective ratings of stress when combining a broadband noise stimulus played at 85–95 dB(A) with a 5 Hz WBV (presented in the Z direction at vibration magnitudes of 2.12 m/s^2 and 2.44 m/s^2) compared with presenting either of these stimuli in isolation. The results further showed an increase in perceived stress from an exposure to sinusoidal vibrations at a resonant frequency compared with a stochastic broadband vibration. Moreover, noise seemed to increase further the experience of stress when the temperature was between 30 °C and 35 °C but only when combined with the stochastic broadband vibration.

Perceived annoyance is another variable studied in this field. Here, results are congruent, indicating that noise and vibration interact to increase subjective ratings of annoyance (see, for example, references [**7**] to [**10**] and [**15**]). Howarth and Griffin [**7**, **8**] showed that this interaction appears to depend on the relative magnitude of the stimuli when exposing participants to 36 different combinations of noise and WBV (noise stimuli ranging between 54 dB(A) and 79 dB(A) with vibration dose values between 0.07 m/s$^{1.75}$ and 0.40 m/s$^{1.75}$ with weighted r.m.s. acceleration averaged over 24 s duration between 0.020 m/s^2 and 0.125 m/s^2). Indeed, the annoyance ratings were lower when participants where exposed to a high-level noise together with a low-magnitude vibration (antagonist effect). On the other hand, a synergistic effect was observed when both the noise level and the vibration magnitude are high.

Studies of the psychological effects of combined noise and WBV exposure are few and conclusions are therefore perilous to draw, a limitation applying to studies examining the psychological effects of WBV presented in isolation. The paucity of studies in this field, the wide variations in the physical characteristics of the stimuli used (Table 1), the methodological disparities between studies with respect to the type of measure used (subjective rating or objective empirical measurement), the heterogeneity of the tasks, and their variable ecological validity does not allow any firm conclusion to be drawn regarding the impact of combined noise and vibration on performance. On balance, however, several studies did report significant effects of WBV and some indication of enhanced effects when presented in combination with noise. Further work is clearly needed if a more systematic view is to be achieved, and more so still if the aim is to form a theoretical account of these effects. The latter point is worth emphasizing as most past studies, when detecting an effect of WBV on performance or subjective ratings of psychological concepts, have not attempted to explore the causal mechanisms underpinning these effects. For example, it is as yet unknown whether the exposure to WBV reduces cognitive performance in a given task owing to direct interference with the mental mechanisms underpinning that task, or whether mediating factors may be at play (e.g. the participants become distracted by their increasing feeling of annoyance).

If further research is clearly needed, identifying specific avenues for research may be desirable. One possible way forward may be to identify factors of theoretical relevance highlighted in connected fields of study. In this respect, noise research appears especially interesting for two reasons. First, noise constitutes, like vibration, a physical stimulus to which field workers are routinely exposed and which they can rarely eliminate. Second, noise research is a considerably more developed field of research and has led to the identification of a series of psychological concepts that have helped to shape theoretical accounts and to formulate safety guidelines.

In the next section, some recent findings from sound and noise research studies, their well-established effects on cognitive performance, as well as a description of some related theoretical contentions are briefly discussed.

4 NEW AVENUES FOR VIBRATION RESEARCH: LESSONS FROM NOISE RESEARCH

Sound and vibration often go together and form part of the same group of physical stimuli produced by many mechanical devices. Yet more is known about the impact of sound on cognitive performance than about the impact of vibration. In this section, recent theoretical concepts emerging from research on noise and performance are identified, and it is suggested that these may offer interesting avenues for future vibration research. The aim is to highlight the type of cognitive functions and tasks that have proven to be sensitive to noise, as potential good candidates for future experiments on the effects of vibration. Designing new research based on theoretical concepts identified in noise research offers not only specific methodological pointers but also, ultimately, valuable information for the development of an overarching theory of performance and distraction.

Studies of the susceptibility of participants' performance and psychological state to noise and sound exposure are numerous and span many types of environment and experimental condition. The results emerging from that literature show that outcomes of noise exposure may depend on specific features of the noise stimulus and the nature of the cognitive tasks performed. In addition to hearing impairments, noise has many other negative consequences that impact on a worker's occupational load. During the 1980s, a range of studies focused on the effect yielded by noise sources carrying little or no information to the listener. For example, some studies found degraded performance in different cognitive tasks when participants were exposed to a continuous free-field noise generated between 125 Hz and 4000 Hz and played at 75 dB(A), 78 dB(A), or 85 dB(C) [**32–34**]. Such noise has been shown to affect performance negatively in focused attention tasks [**32**], in search-and-memory tasks [**33**], and in detection tasks [**34**].

Early noise research distinguished between the characteristics of the noise and the nature of the task being performed by participants. With respect to the first, Loeb [**35**] suggested that the effects of noise on performance can be distinguished on the basis of the noise's meaningfulness, the affective value, and a number of physical characteristics (intermittency, frequency, duration, and intensity). Numerous findings suggest that both aspects must be considered together, however. For example, the greater impact of meaningful sound compared with white noise is especially evident in tasks requiring information processing, such as short-term memory tasks requiring the encoding, temporary maintenance, and recall of information (see, for example, references [**36**] and [**37**]). Many more recent studies have documented more subtle effects and their dependence on specific sound characteristics. For example, disruption in certain cognitive tasks depends largely on changes in pitch, timbre, or tempo, while noise level does not seem to have much influence on performance (see, for example, references [**38**] and [**39**]).

One area of cognition repeatedly shown to be adversely affected by auditory distracters of various types (which participants are instructed to ignore) is short-term memory. In particular, the ability of individuals to encode, maintain, and recall information in order (a type of memory referred to as 'serial memory'). This ability is an essential aspect of most cognitive functions, from language to memory or motor control (see, for example, reference [**40**]) that has proved particularly susceptible to auditory distracters. One important and recent theoretical development follows from the observation that sound containing changing utterances or tones is more disruptive than monotonous or repeated sound. Numerous studies have demonstrated that this effect of task-irrelevant sounds is observed as long as these irrelevant sounds are perceived as a coherent auditory stream [**41**, **42**] and are perceptually distinct and changing across time [**43**, **44**]. This 'changing-state' characteristic of the sound, rather than its semantic content, appears to be the fundamental determinant of disruption of order memory by sound. Remarkably, the effect of irrelevant sound on cognitive serial memory is observed not only when sound is presented during the encoding of to-be-remembered stimuli but also when presented after this encoding phase and before participants recall the content of their memory (see, for example, reference [**4**]). The processing of order information is a fundamental pillar of many cognitive abilities, from conditioning to more complex functions (see, for example, reference [**40**]), making such findings relevant for many complex applied settings. Furthermore, Jones [**45**] also argued that the effect of irrelevant sound is not limited to short-term memory but also affects a range of complex cognitive abilities such as those measured in mental arithmetic, problem solving, and reasoning tasks. These conclusions are based on controlled laboratory experiments and are convergent with the results of field studies. For example, both Hygge *et al.* [**46**] and Enmarker [**47**] investigated the exposure of recorded meaningful irrelevant speech (approximately 62 dBA with a dominant frequency range between 500 Hz and 1.55 Hz) and a recorded road traffic noise (approximately 62 dBA with a dominant frequency range between 100 Hz and 300 Hz) on different memory abilities. Both studies found that performance in a cued recall task measuring episodic memory (detailed memory for specific events and their spatial and temporal context) was negatively, and equally, affected by the exposure to both traffic noise and speech. In line with laboratory studies of the impact of sound on cognitive performance, Hygge *et al.* [**46**] and Enmarker [**47**] concluded that the impairment which they observed related to changes in the acoustic characteristics of the sound, irrespective of its nature (speech versus non-speech). Overall, therefore, cognitive studies on the effect of noise suggest that the changing nature of sound is an important predictor of their distractive potency.

Most studies on the cognitive impact of noise focused on the degradation of performance during the exposure to the sound. After-effects, on the other hand, have received relatively little attention, despite the well-established finding of after-effects following exposure to a range of other environmental factors (e.g. movements of a ship). Glass and Singer [**48**] and Glass *et al.* [**49**] published two of the first studies documenting the after-effects caused by environmental noise (urban noise) exposure on mental task performance. According to these researchers, two factors were of major importance in yielding this after-effect: the uncontrollable nature of the sound and the unpredictability of sound. Interestingly, the unpredictability of sound has been at the heart of a tradition of research investigating the involuntary capture of attention by task-irrelevant sound. Numerous studies have reported that an unexpected change in the background sound elicits an automatic and rapid brain response in the form of a negative wave measured by electrodes applied to the scalp of participants (see, for example, reference [**50**]). This brain wave, termed the mismatch negativity, is interpreted as the signature of a change detection mechanism thought to be of critical importance to allow some auditory signals to break through selective attention. This attentional interruption system is particularly useful to alert a person to the presence of a potential danger, or a change in our environment that may prove important to notice (e.g. a sudden change in the sound produce by a vehicle's engine). Remarkably, sudden changes in the auditory environment have also been found to disrupt cognitive performance in simple categorization tasks (see, for example, reference [**51**]) as well as more demanding tasks such as serial recall [**52**, **53**]. Finally, it is worth noting that the distractive effect of sudden changes in a stream of stimuli is not limited to the auditory modality but has also been reported in electrophysiological studies using tactile and visual stimuli [**54**–**58**].

The finding of after-effects of noise exposure is potentially of great importance to examine the effect of noise and vibration in applied settings because many such settings involve intermittent noise and vibration and require operators to perform various mental tasks in the presence of these stressors but also following a period of exposure. For example, many vehicle drivers are exposed to noise and vibration for various durations several times during a work shift. Any degradation in cognitive performance after the exposure during a driving shift might have direct negative consequences for the worker's health or influence their performance between work shifts. Little attention has been paid to this issue outside a very limited set of studies. For example, Kjellberg *et al.* [**59**] studied noise exposure, fatigue, and performance in airplane mechanics and crews of ships from a coastal fleet (noise exposures in three groups was less than 60 dB(A) for 20 645 participants, 60–80 dB(A) for 17 545 participants, and greater than 80 dB(A) for 3252 participants). Of interest for the purpose of the present review is the finding of a negative effect of high environmental noise exposure (A-weighted equivalent sound level varied between 95 dB(A) and 102 dB(A) but all workers wore hearing protectors) on reaction times in a mental task measured after a work shift. Furthermore, this effect was still observed several days later (see reference [**60**] for similar results). Kjellberg *et al.* discussed the possibility that the WBV caused by the ship (centred around 2 Hz) might have contributed to the effects.

The existence of after-effects caused by noise should be of interest to WBV researchers because vehicle environments involve both noise and WBV exposure. As pointed out by Cohen [**61**] in one of the early studies reporting after-effects, it is unlikely that behavioural after-effects are caused by one stressor only. Rather, after-effects are more likely to be caused by multiple stressors. Moreover, Ljungberg and Neely [**5**] showed that noise is not unique in yielding after-effects. Indeed, these workers found that WBV similar to that encountered in heavy vehicles can cause after-effects in the form of a decline in attention when the exposure to WBV was accompanied by tasks imposing a high mental load on participants. Given that many vehicle environments involve multiple sources of stressors (WBV, noise, and mental load), further research on after-effects from combined noise and WBV would clearly be beneficial from theoretical and applied perspectives.

In summary, past research shows that noise can affect a number of psychological variables such as stress, fatigue, and annoyance, as well as performance in a number of cognitive tasks, especially tasks involving the processing of information in order, and when this sound includes variations in content and is unpredictable. These findings highlight a number of possible avenues for research on WBV and their combined effect with that of noise. Specifically, it may be useful to establish the extent to which the temporal characteristics (e.g. amount and predictability of change across time) of the vibration mediate their impact on performance and variables such as fatigue, annoyance, or stress. The unpredictability of the vibration may also prove to be important, owing to either its physical impact (because the operator's body has to adjust to a sudden movement of the vehicle's cabin), or its cognitive consequences (e.g. because the operator has to interrupt an ongoing action to deal with a potentially urgent change in his or her work environment, such as when a change in vibration may signify the impact of the vehicle against an obstacle or a mechanical failure). Overall, it would be useful to explore the effect of WBV on performance by examining systematically the following, as has been done for noise:

(a) the meaning and physical characteristics of the vibrations;
(b) the degree of predictability of the vibration;
(c) the type of mental processes being performed in a task;
(d) the role of potential mediating subjective factors such as annoyance and fatigue.

With such data available, not only may predictions begin to be made about application areas most susceptible to suffer adverse effects of WBV on performance but also similarities and differences between different classes of physical stimuli may be established in order to build a more integrated theory of performance and distraction.

5 DISCUSSION

A key aim of this review was to summarize past research on the psychological effects of combined noise and WBV. A second goal was to bring to light methods and findings from the research on noise and its cognitive effects, in order to stress possible new paths for WBV research as a single stressor or combined with noise. The need for further research on the combined effects of noise and WBV is justified by the fact that many workers (drivers in particular) are exposed to noise and WBV simultaneously, often in conditions of high mental load. Reduced performance while operating a vehicle impacts on work efficiency and increases the risk of accident. Furthermore, the international standards and regulations that set adequate occupational exposure levels for noise and WBV do not consider the likelihood of any interactions between these two stressors [**1**, **2**], and no guidelines are provided that address possible effects of noise or WBV exposure on mental tasks [**1**, **2**, **62**].

Focusing solely on working environments and vehicle settings in general, many of the studies conducted so far suffer from low ecological validity. As a consequence, our understanding of the psychological effects of WBV remains rather limited. Unrealistic noise levels have often been presented to participants and the WBV stimulus has often, in early studies, been presented as vibration in one direction only, with inconclusive results (see, for example, references [**6**], [**25**], [**26**], and [**28**]). In a few studies conducted more recently and using more realistic WBV (e.g. based on field recordings), no clear effect of combined noise and vibration on performance was found (see, for example, references [**4**], [**5**], [**15**], and [**24**]). However, so far, the conclusion that can be drawn from early studies is that some cognitive tasks have proved to be sensitive to combined effects of noise and WBV (e.g. a complex counting task [**27**]). Yet, adequate studies are too scarce to draw any firm conclusion at this stage. Further limitations include the use of physical stimuli differing from those observed in real-life settings and their use over relatively short exposure durations (often shorter than an hour; thereby also ruling out the possibility of observing potential cumulative effects). Finally, even though statistically significant effects have been found in some studies, the size of these effects is seldom commented upon and so it is difficult to assess what impact WBV may have in the field. However, careful examination of past studies shows, as presented in Table 1, that decrements in performance are observed in several types of task following exposure to vibration, noise, or their combination. The exposure to vibration stimuli does appear to decrease motor tracking abilities by around 22 per cent on average (based on six studies). Conclusions are difficult to draw for other cognitive tasks since different studies used different tasks. However, the reduction in performance in those is not negligible, especially for tasks taxing selective attention (15.9 per cent) and mental arithmetic (28 per cent). With respect to ratings, vibration increases annoyance, stress, and difficulty ratings to a relatively large extent (51.4–75.5 per cent), while ratings of alertness exhibit a more modest but not inconsequential (14.5 per cent on average).

The tasks used in most of these studies (from investigations of the effects of both WBV and combined noise and WBV) have often been related to the mental functions required for operating certain vehicles such as motor control tasks (see, for example, references [**25**] and [**26**]) or reading (see, for example, reference [**16**]), but less research has been conducted to examine higher cognitive functioning such as the control of attention and short-term memory. These functions deserve consideration, however, as interference with short-term memory caused by external stimuli may affect negatively the operation of a vehicle and cause errors or even accidents [**63**]. The need to examine higher cognitive functions is made more evident by the fact that the few studies that did find effects of combined exposures to WBV and noise on performance did so using tasks requiring such functions (e.g. complex counting task [**27**]). Mental arithmetic tasks are not a part of the typical driving situation, but the underlying mental processes underpinning performance in such tasks (e.g. executive functions and short-term memory [**64**]) may potentially be present in a variety of working environments.

Research on the psychological effects of noise have generated a number of findings and theoretical ideas that may benefit further research on the effects yielded by WBV exposure, whether presented in isolation or in combination with noise. A number of studies showed that task-irrelevant sound, under certain perceptual constraints (e.g. segmentation and change over time) (see, for example, reference [**44**]), affects the processing of order information, a mental function that is crucial to a large range of human behaviours. Future research on WBV may therefore benefit from examining in greater detail the role of the physical characteristics of the vibration as well as, and in combination with, the nature of the mental processes at play in specific tasks. Finally, given the evidence for the disruptive effect of unexpected auditory changes on performance in tasks of varying difficulty (see, for example, reference [**65**]), research on WBV may also benefit from further research measuring the effect of the unpredictability of changes in the WBV stimuli (e.g. intensity).

Subjective measurements (such as measurements of stress, annoyance, or fatigue) have, on the other hand, proven to be more sensitive to the short-term effect of noise and vibration than behavioural indices of cognitive performance in certain laboratory studies. For example, combined noise and WBV are perceived by participants as a negative experience (see, for example, references [**7**], [**15**], and [**31**]). Such psychological effects may possibly lead to a decrease in performance in the long run, but there is, to date, no systematic study addressing this issue. On that basis, the exposure time should be considered not only as an important parameter when designing experiments, but also for the generalization of the results. Most studies on the effects of combined noise and WBV have been controlled laboratory studies in which exposure times have been relatively short. Using an exposure time similar to those encountered in real work settings may potentially unearth psychological effects and performance decrements not observed yet.

One area clearly deserving further work is critical assessment of the relationship between subjective and empirical data, for the two do not always correlate (see, for example, references [**4**], [**5**], and [**66**]). It may be questioned whether tasks used in past studies have been sensitive enough or not demanding enough and allowed participants to use coping strategies to overcome the potential effect of WBV. Coping strategies have not been considered in past research but may account for the intermittent discrepancy between subjective ratings and performance. For instance, the gathering of mental resources in order to overcome interference from vibration may result in feelings of fatigue and annoyance. Increasing the exposure time within the feasible limits of laboratory settings may constitute a way to enhance the probability to detect possible effects on some of the tasks used. An alternative avenue for research may lie in the adoption of tasks and stimuli characteristics successfully used in other fields such as noise research. Finally, future studies would benefit from including both empirical and subjective measures of performance as recently reported in noise research. For example, Zimmer *et al.* [**67**] found a relationship between the degradation in their participants' performance in a serial recall task in the presence of task-irrelevant sound and their reported levels of annoyance (measured by subjective ratings), such that their subjective rating of annoyance increased in conditions in which noise reduced memory performance.

Studying further the possible short-term effects of noise and WBV on cognitive performance (such as that measured in short-term memory tasks) does not address the issue of potential long-term effects but, first, would help to broaden understanding of the fundamental principles underpinning distraction by physical stimulation and, second, would offer potential implications for certain work environments. For example, short-term memory and attentional control have been shown to be of importance to manoeuvre a car safely [**63**].

Lasting effects resulting from long-term exposure to WBV should also be considered, since WBV may, according to some studies, yield effects that outlast the exposure to vibration. In that respect, the conclusions drawn from a number of early studies on noise after-effects may be informative (see, for example, reference [**59**]). In line with the conclusions of Cohen [**61**] that after-effects are rarely caused by only one stressor, WBV can induce after-effects in an attentional task when WBV occurs during a period of high mental load [**5**]. Mental after-effects caused by noise or WBV have potential implications for applied research. For example, many vehicle drivers are exposed to noise and vibration for various periods of time, several times throughout a work shift. Any decline in cognitive performance after exposure but during a driving shift may impair the drivers' performance in tasks that they undertake shortly afterwards.

With a driver of a heavy vehicle in mind, what are the potential implications of past studies on the combined effects of noise and WBV on mental load, subjective experience, and performance? If the scarce existing findings can be generalized to real-life situations, the combination of noise and WBV exposure may degrade the cognitive performance of workers, possibly as a by-product of an increase in stress, annoyance, or fatigue. Motor control but also more demanding tasks (such as those requiring calculations) may be disrupted, possibly as a function of the exposure levels, the changing nature of the vibrations, and the mental load experienced by drivers. While no systematic data are available documenting the long-term psychological effects of exposure to WBV, it may be hypothesized that high levels of annoyance, stress, and fatigue may lead to a reduction in the ability of drivers to concentrate. Importantly, some data suggest that WBV can induce effects on cognitive performance even after the exposure. This should be considered in the programming of work shifts and preparation of safety guidelines. Further research is needed to explore these issues, however.

ACKNOWLEDGEMENT

Financial support from the Heart and Lung Foundation in Örnsköldsvik and from Luleå University of

Technology is gratefully acknowledged. Jessica K. Ljungberg is an Honorary Research Fellow at the School of Psychology, Cardiff University, UK. Fabrice Parmentier is an External Research Associate at the School of Psychology, University of Western Australia.

REFERENCES

1 ISO 2631-1:1997 *Mechanical vibration and shock – evaluation of human exposure to whole body vibration – Part 1: general requirements*, 1997 (International Organization for Standardization, Geneva).

2 ISO 1999:1990 *Acoustics – determination of occupational noise exposure and estimation of noise-induced hearing impairment*, 1990 (International Organization for Standardization, Geneva).

3 **Sherwood, N.** and **Griffin, M. J.** Effects of whole-body vibration on short-term memory. *Aviat. Space Environ. Med.*, 1990, **61**, 1092–1097.

4 **Ljungberg, K. J.** and **Neely, G.** Stress, subjective experience and cognitive performance during exposure to noise and vibration. *J. Environ. Psychol.*, 2007, **27**, 44–54.

5 **Ljungberg, K. J.** and **Neely, G.** Cognitive after-effects of vibration and noise exposure and the role of noise sensitivity. *J. Occup. Health*, 2007, **49**, 111–116.

6 **Sommer, H. C.** and **Harris, C. S.** Combined effects of noise and vibration on human tracking performance and response time. *Aerospace Med.*, 1973, **44**, 276–281.

7 **Howarth, H. V. C.** and **Griffin, M. J.** Subjective response to combined noise and vibration: summation and interaction effects. *J. Sound Vibr.*, 1990, **143**(3), 443–454.

8 **Howarth, H. V. C.** and **Griffin, M. J.** The relative importance of noise and vibration from railways. *Appl. Ergonomics*, 1990, **21**(2), 129–134.

9 **Nakamura, H., Nohara, S., Nakamura, H., Kajikawa, Y.,** and **Okada, A.** Field study on subjective responses to noise and vibration. *Arch. Complex Environ. Stud.*, 1990, **2**(3), 25–32.

10 **Paulsen, P.** and **Kastka, J.** Effects of combined noise and vibration on annoyance. *J. Sound Vibr.*, 1995, **181**(2), 295–314.

11 **Rehn, B.** *Musculoskeletal disorders and whole-body vibration exposure: among professional drivers of all-terrain vehicles*. Doctoral Thesis, Umeå University, Umeå, Sweden, 2004.

12 **Rehn, B., Nilsson, T., Olofsson, B.,** and **Lundström, R.** Whole-body vibration exposure and non-neutral neck postures during occupational use of all-terrain vehicles. *Ann. Occup. Hyg.*, 2005, **49**(3), 267–275.

13 **Seidel, H., Harazin, B., Pavlas, K., Sroka, C., Richter, J., Bluthner, R., Erdmann, U., Grzesik, J., Hinz, B.,** and **Rothne, R.** Isolated and combined effects of prolonged exposures to noise and whole-body vibration on hearing, vision and strain. *Int. Arch. Occup. Environ. Health*, 1988, **61**, 95–106.

14 **Mansfield, N. J.** *Human response to vibration*, 2005 (CRC Press, Boca Raton, Florida).

15 **Ljungberg, J., Neely, G.,** and **Lundström, R.** Cognitive performance and subjective experience during combined exposure of whole-body vibration and noise. *Int. Arch. Occup. Environ. Health*, 2004, **77**, 217–221.

16 **Griffin, M. J.** and **Hayward, R. A.** Effects of horizontal whole-body vibration on reading. *Appl. Ergonomics*, 1994, **25**(3), 165–169.

17 **Kjellberg, A.** Psychological aspects of occupational vibration. *Scand. J. Work, Environ. Health*, 1990, **16**(1), 39–43.

18 **Conway, G. E., Szalma, J. L.,** and **Hancock, P. A.** A quantitative meta-analytic examination of whole-body vibration effects on human performance. *Ergonomics*, 2007, **50**(2), 228–245.

19 **Abbate, C., Micali, E., Giorgianni, C., Munao, F., Brecciaroli, R., Salmaso, L.,** and **Germano, D.** Affective correlates of occupational exposure to whole-body vibration. A case-control study. *Psychotherapy Psychosomatics*, 2004, **73**(6), 375–379.

20 **Webb, R. D. G., Bennett, M. D., Farmilo, B., Cole, S. H., Page, S. J.,** and **Withey, W. R.** Personality and inter-subject differences in performance and physiological cost during whole-body vibration. *Ergonomics*, 1981, **24**(4), 245–255.

21 **Neely, G., Lundström, R.,** and **Björkvist, B.** Sensation seeking and subjective unpleasantness ratings of stimulus intensity. *Perceptual Motor Skills*, 2002, **95**, 706–712.

22 **Sherwood, N.** and **Griffin, M. J.** Evidence of impaired learning during whole-body vibration. *J. Sound Vibr.*, 1992, **152**(2), 219–225.

23 **Newell, G. S.** and **Mansfield, N. J.** Evaluation of reaction time performance and subjective workload during whole-body vibration exposure while seated in upright and twisted postures with and without armrests. *Int. J. Ind. Ergonomics*, 2008, **38**, 499–508.

24 **Ljungberg, K. J.** Cognitive degradation after exposure to combined noise and whole-body vibration in a simulated vehicle ride. *Int. J. Veh. Noise Vibr.*, 2007, **3**(2), 130–142.

25 **Grether, W. F., Harris, C. S., Mohr, G. C., Nixon, C. W., Ohlbaum, M., Sommer, H. C., Thaler, V. H.,** and **Veghte, J. H.** Effects of combined heat, noise and vibration stress on human performance and physiological functions. *Aerospace Med.*, 1971, **42**(10), 1092–1097.

26 **Grether, W. F., Harris, C. S., Ohlbaum, M., Sampson, P. A.,** and **Guignard, J. C.** Further study of combined heat, noise and vibration stress. *Aerospace Med.*, 1972, **43**(6), 641–645.

27 **Harris, S. C.** and **Shoenberger, R. W.** Combined effects of broadband noise and complex waveform vibration on cognitive performance. *Aviation Space Environ. Med.*, 1980, **51**(1), 1–5.

28 **Sandover, J.** and **Champion, D. F.** Some effects of a combined noise and vibration environment on a mental arithmetic task. *J. Sound Vibr.*, 1984, **95**(2), 203–212.

29 **Baddeley, A. D.** A 3-min reasoning test based on grammatical transformation. *Psychonomic Sci.*, 1968, **10**(10), 341–342.

30 **Sternberg, S.** High speed scanning in human memory. *Science*, 1966, **53**, 652–654.

31 **Manninen, O.** Further studies on changes in subjective stressfulness under various combinations of noise, vibration, temperature and work tasks. *Arch. Complex Environ. Stud.*, 1990, **2**(2), 31–39.

32 **Smith, A. P.** Acute effects of noise exposure: an experimental investigation of the effects of noise and task parameters on cognitive vigilance tasks. *Int. Arch. Occup. Environ.*, 1988, **60**, 307–310.

33 **Smith, A. P.** Noise and aspects of attention. *Br. J. Psychol.*, 1991, **82**, 313–324.

34 **Smith, A. P.** and **Miles, C.** The combined effects of occupational health hazards: an experimental investigation of the effects of noise, night-work and meals. *Int. Arch. Occup. Environ.*, 1987, **59**, 83–89.

35 **Loeb, M.** *Noise and human efficiency*, 1986 (John Wiley, Chichester, West Sussex).

36 **Colle, H. A.** Auditory encoding in visual short-term recall: effects of noise intensity and spatial location. *J. Verbal Learning Verbal Behav.*, 1980, **19**, 722–735.

37 **Smith, A. P.** The effects of different types of noise on semantic processing and syntactical reasoning. *Acta Psychol.*, 1985, **58**, 263–273.

38 **Hughes, R.** and **Jones, D. M.** The intrusiveness of sound laboratory findings and their implications for noise abatement. *Noise Health*, 2001, **4**(13), 51–70.

39 **Jones, D. M.** and **Macken, W. J.** Auditory babble and cognitive efficiency: role of number of voices and their location. *J. Expl Psychol.: Appl.*, 1995, **1**, 216–226.

40 **Lashley, K. S.** The problem of serial order in behavior. In *Cerebral mechanisms in behavior. The Hixon symposium* (Ed. L. A. Jeffress), 1951, pp. 112–146 (John Wiley, New York).

41 **Jones, D. M., Saint-Aubin, J.,** and **Tremblay, S.** Modulation of the irrelevant sound effect by organizational factors: further evidence from streaming by location. *Q. J. Expl Psychol. A: Hum. Expl Psychol.*, 1999, **52**, 545–554.

42 **Jones, D. M.** and **Macken, W.** Irrelevant tones produce an irrelevant speech effect: implications for phonological coding in working memory. *J. Expl Psychol.: Learning, Memory Cognition*, 1993, **19**, 369–381.

43 **Jones, D. M., Madden, C.,** and **Miles, C.** Privileged access by irrelevant speech: the role of changing state. *Q. J. Expl Psychol. A: Hum. Expl Psychol.*, 1992, **44**, 645–669.

44 **Tremblay, S.** and **Jones, D. M.** Role of habituation in the irrelevant sound effect: evidence from the effects of token set size and rate of transition. *J. Expl Psychol.: Learning, Memory Cognition*, 1998, **24**, 659–671.

45 **Jones, D. M.** Recent advances in the study of human performance in noise. *Environ. Int.*, 1990, **16**, 447–458.

46 **Hygge, S., Boman, E.,** and **Enmarker, I.** The effects of road traffic noise and meaningful irrelevant speech on different memory systems. *Scand. J. Psychol.*, 2003, **44**(1), 13–21.

47 **Enmarker, I.** The effects of meaningful irrelevant speech and road traffic noise on teachers' attention, episodic and semantic memory. *Scand. J. Psychol.*, 2004, **45**, 393–405.

48 **Glass, D. C.** and **Singer, J. E.** *Urban stress: experiments on noise and social stressors*, 1972 (Academic Press, New York).

49 **Glass, D. C., Singer, J. E.,** and **Friedman, L. N.** Psychic cost of adaptation to an environmental stressor. *J. Personality Social Psychol.*, 1969, **12**, 200–210.

50 **Näätänen, R.** The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function. *Behav. Brain Sci.*, 1990, **13**, 201–288.

51 **Parmentier, F. B. R.** Towards a cognitive model of distraction by auditory novelty: the role of involuntary attention capture and semantic processing. *Cognition*, 2008, **109**, 345–362.

52 **Hughes, R. W., Vachon, F.,** and **Jones, D. M.** Disruption of short-term memory by changing and deviant sounds – support for a duplex-mechanism account of auditory distraction. *J. Expl Psychol.: Learning, Memory Cognition*, 2007, **33**, 1050–1061.

53 **Ljungberg, K. J., Hughes, R., Macken, W.,** and **Jones, D. M.** Listen up! Dissociations between behavioral and subjective responses to auditory alarms, 2010 (to be published).

54 **Downar, J., Crawley, A. P., Mikulis, D. J.,** and **Davis, K. D.** A multimodal cortical network for the detection of changes in the sensory environment. *Nature Neurosci.*, 2000, **3**, 277–283.

55 **Downar, J., Crawley, A. P., Mikulis, D. J.,** and **Davis, K. D.** A cortical network sensitive to stimulus salience in a neutral behavioral context across multiple sensory modalities. *J. Neurophysiol.*, 2002, **87**, 615–620.

56 **Knight, R. T.** Contributions of human hippocampal region to novelty detection. *Nature*, 1996, **383**, 256–259.

57 **Yamaguchi, S.** and **Knight, R. T.** Age effects on the P300 to novel somatosensory stimuli. *Electroencephalogr. Clin. Neurophysiol.*, 1991, **78**, 297–301.

58 **Yamaguchi, S.** and **Knight, R. T.** P300 generation by novel somatosensory stimuli. *Electroencephalogr. Clin. Neurophysiol.*, 1991, **78**, 50–55.

59 **Kjellberg, A., Muhr, P.,** and **Sköldström, B.** Fatigue after work in noise – an epidemiological

survey study and three quasi-experimental field studies. *Noise Health*, 1998, **1**, 47–55.

60 **Lindström, K.** and **Mäntysalo, S.** Attentive behaviour after exposure to continuous industrial noise. In *Machine pace and occupational stress* (Eds G. Salvendy and M. J. Smith), 1981, pp. 91–96 (Taylor & Francis, London).

61 **Cohen, S.** After-effects of stress on human performance and social behaviour: A review of research and theory. *Psychol. Bull.*, 1980, **88**(1), 82–108.

62 ISO 9612:1997 *Acoustics – guidelines for the measurement and assessment of exposure to noise in a working environment*, 1997 (International Organization for Standardization, Geneva).

63 **Gugerthy, L.** Situation awareness during driving: explicit and implicit knowledge in dynamic spatial memory. *J. Expl Psychol.: Appl.*, 1997, **3**, 42–66.

64 **DeStefano, D.** and **LeFevre, J.-A.** The role of working memory in mental arithmetic. *Eur. J. Cognitive Psychol.*, 2004, **16**, 353–386.

65 **Parmentier, F. B. R., Elford, G., Escera, C., Andrés, P.,** and **San Miguel, I.** The cognitive locus of distraction by acoustic novelty in the cross-modal oddball task. *Cognition*, 2008, **106**, 408–432.

66 **Persson Waye, K., Bengtsson, J., Kjellberg, A.,** and **Benton, S.** Low frequency noise 'pollution' interferes with performance. *Noise Health*, 2001, **4**(13), 33–49.

67 **Zimmer, K., Ghani, J.,** and **Ellermeier, W.** The role of task interference and exposure duration in judging noise annoyance. *J. Sound Vibr.*, 2008, **311**, 1039–1051.