Understanding noise stress-induced cognitive impairment in healthy adults and its implications for schizophrenia

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Abstract

Noise stress (NS) is detrimental to many aspects of human health and behavior. Understanding the effect of noise stressors on human cognitive function is a growing area of research and is crucial to helping clinical populations, such as those with schizophrenia, which are particularly sensitive to stressors. A review of electronic databases for studies assessing the effect of acute NS on cognitive functions in healthy adults revealed 31 relevant studies. The review revealed (1) NS exerts a clear negative effect on attention, working memory and episodic recall, and (2) personality characteristics, in particular neuroticism, and sleep influence the impact of noise stressors on performance in interaction with task complexity. Previous findings of consistent impairment in NS-relevant cognitive domains, heightened sensitivity to stressors, elevated neuroticism and sleep disturbances in schizophrenia, taken together with the findings of this review, highlight the need for empirical studies to elucidate whether NS, a common aspect of urban environments, exacerbates cognitive deficits and other symptoms in schizophrenia and related clinical populations.

Keywords: *Cognitive deficits, literature review, noise stress*

Introduction

Noise pollution is an aspect of the urban environment that has been shown to impair cognitive performance in non clinical populations.[1] This effect is evident for many different cognitive functions, for example, sustained attention,[2] inhibition of pre-potent responses[3] and episodic memory,[4] that are known to be impaired, on average, in patients diagnosed with schizophrenia. There is now a wealth of data demonstrating that cognitive dysfunction is intrinsic to schizophrenia[5,6] and a stronger predictor of social and vocational functioning than the severity of negative and positive symptoms.[7,8] Given the central role of cognitive function in determining the outcome in patients with psychosis, it is important to uncover environmental variables that may impair cognitive reserve in real-life settings. One such variable is likely to be noise stress (NS).

Access this article online	
Quick Response Code:	Website: www.noiseandhealth.org
	DOI: 10.4103/1463-1741.134917

The primary aim of this review is to (1) consider the noise characteristics that are perceived as unpleasant and found to be detrimental to human cognitive performance, (2) examine individual differences variables that moderate the observed or perceived effects of noise, (3) review undesirable effects of environmental noise on specific cognitive domains in healthy adults, (4) discuss the relevance of findings from (2) and (3) in the context of schizophrenia, and (5) identify directions for future research capable of answering important questions concerning the effect of noise pollution on cognitive functions, particularly in schizophrenia.

The characteristics of noise that make it a stressor

Noise stressors are a component of an adverse environment encountered at higher levels in urban areas. Different types of noise stressors commonly experienced in urban environments are transportation noise (cars, airports, trains), workplace noise (building sites, busy office spaces), and home and social noise (busy cafes, constantly running televisions, conversations). It was estimated in 2009 that 55% of the UK population[9] live in environmental noise levels exceeding the guidelines set by the World Health Organization (WHO).[10] The Parliamentary Office of Science and Technology Environmental Noise article[11] quantifies a noise's unpleasantness as depending on its "loudness, frequency, content, duration, intermittence, predictability and source". WHO recommend that "to avoid hearing impairment, impulse noise exposure should never exceed a peak sound level of 140 dB peak in adults," while daily 1 hour exposure of listening to music through headphones should not exceed 85 dB [for a complete set of guidelines, Appendix 1]. As well as medical guidelines, psychosomatic advisory guidelines have also been set, at 50-55 dBa, to avoid moderate annoyance.

In research studies focused on quantifying the effect of noise in human cognition, the noise levels used never reach the recommended top peak level of 140 dB, most likely for ethical and health reasons, with sounds commonly falling within a peak range of 60-100 dB. The levels of sound selected in studies tend to depend on the content of the sound. When white noise is used, noise level exposure is commonly over 90 dB.[12,13] When using environmentally realistic noise (such as an airport or busy roads), noise levels used in most studies are much lower, between 60 and 80 dB.[14] The trend in research is now to use a range of environmental realistic noises such as traffic, aircraft, or noise consisting of speech, as opposed to continuous white noise, to increase ecological validity.

Despite the WHO guidelines,[10] it is difficult to give a concrete definition of the characteristics of noise that make it a "stressor," as opposed to acceptable background noise. This is due to the variability of noise stimuli used in previous studies and the added problem that noise that is stressful to one individual may be tolerable to another.

Individual differences in noise sensitivity

Job[15] defines noise sensitivity as "the internal states (be they physiological, psychological [including attitudinal], or related to lifestyle or activities conducted) of any individual, which increase their degree of reactivity to noise in general." Noise sensitivity can be measured by gaining self-reports from participants or by comparing performance or physiological indices in the presence and absence of noise, and is normally unrelated to auditory acuity.[16]

Individuals who report they are highly noise sensitive, compared to those who report low noise sensitivity, have been found to have reduced work ability and attention;[17] though self-reported measures of noise sensitivity do not always correlate with objective impairment of performance under noise conditions.[18,19] Noise sensitivity also correlates with affective indices, most notably annoyance and irritation.[19] There appear to be two types of noise sensitive individuals: Those who display noise-induced performance deficits and those who report annoyance and/or perceived disruption due to noise (whether or not this is accompanied by performance deficits).

Individual differences in personality traits and arousal

Personality differences may in part account for the effects of noise sensitivity. For example, there is a known association between personality, in particular neuroticism, and tolerance/sensitivity to noise[20] with neuroticism positively related to subjective noise sensitivity and annoyance during noise.[21] However, any influence of personality may also be mediated by basal arousal as well as arousability. Hockey[22] argued that "noise acts as a general stimulant, and raises the level of arousal" (p. 28). People with high scores on neuroticism scales, relative to stable individuals, are believed to show enhanced

Appendix 1: WHO (1999) guideline values for community noise in specific environments

Specific environment	Critical health effect(s)	LAeq (dB)	Time base (h)	LAmax, fast (dB)
Outdoor living area	Serious annoyance, day-time and evening moderate annoyance, day-time and evening	50-55	16-16	-, -
Dwelling, indoors Inside bedrooms	Speech intelligibility and moderate annoyance, day-time and evening sleep disturbance, night-time	30-35	8-16	45
Outside bedrooms	Sleep disturbance, window open (outdoor values)	45	8	60
School class rooms and preschools, indoors	Speech intelligibility, disturbance of information extraction, message communication	35	During class	—
Preschool bedrooms, indoors	Sleep disturbance	30	Sleeping -time	45
School, playground outdoor	Annoyance (external source)	55	During play	—
Hospital, ward rooms, indoors	Sleep disturbance, night-time			
	Sleep disturbance, day-time and evenings	30-30	8-16	40, -
Hospitals, treatment rooms, indoors	Interference with rest and recovery	#1		
Industrial, commercial, shopping and traffic areas, indoors and outdoors	Hearing impairment	70	24	110
Ceremonies, festivals and entertainment events	Hearing impairment (patrons: <5 times/year)	100	4	110
Public addresses, indoors and outdoors	Hearing impairment	85	1	110
Music through headphones/earphones	Hearing impairment (free-field value)	85 #4	1	110
Impulse sounds from toys, fireworks and firearms	Hearing impairment (adults) hearing impairment (children)	—	—	140 #2, 120 #2
Outdoors in parkland and conservation areas	Disruption of tranquillity	#3		

#1 = Low as possible, #2 = Peak sound pressure (not LAmax, fast), measured 100 mm from the ear, #3 = Existing quiet outdoor areas should be preserved and the ratio of intruding noise to natural background sound should be kept low, #4 = Under headphones, adapted to free-field values arousability, or higher emotional (limbic-system) arousal levels during stress[23,24] and this can explain the replicated finding of their greater sensitivity and lower ability to adapt to noisy conditions.[16]

The interaction of personality traits with the noise- and task-induced arousal (both loud noise and complex tasks being relatively more arousing) could also influence task performance, as can be expected following theories postulating a curvilinear relationship between arousal and performance.[25,26] Based on these theories, an increase in arousal by endogenous (e.g., personality) or exogenous (e.g., noise) variables will help performance on simple tasks but hinder performance on complex tasks. The personality dimension of introversion-extraversion (E) is particularly relevant in this context. It is theorized[27] and has been found empirically,[28] to reflect individual differences in a cortical arousal system: It is chronically more active in introverts relative to extraverts, and influences cognitive performance in interaction with task parameters and environmental manipulations such as noise. Empirical studies support this position in showing, for example, that introverts, relative to extraverts, display more pronounced concentration disruption and fatigue[29] and disrupted logical reasoning performance[30] under noise since they are already optimally aroused for these tasks.

Individual differences in gender, intelligence, and sleep quality

Gender affects an individual's response to noise either directly or indirectly through its effect on other factors. Women, relative to men, show a greater adverse effect of noise for processing speed[31] and vigilance.[32] Such results may at least in part be accounted for by other gender differences, for instance, women on average score higher in anxiety/neuroticism than men.[33] If a sample of women has higher levels of neuroticism and anxiety than men, this may indirectly lead to increases in noise sensitivity and annoyance. Furthermore, intelligence quotient (IQ) may moderate the effect of noise in cognitive performance across both sexes. A high level of within-subject variation in trial-to-trial cognitive performance has been postulated to correlate with lower levels of intelligence,[34,35] thus having a lower IQ may result in less stable performance under noisy conditions.

Sleep disturbances are known to independently impair performance on complex cognitive tasks,[36-39] and this may be exaggerated under noise. However, the presence of noise may also help to counteract the negative effects of acute mild sleep deprivation and drugs that mimic sleep deprivation such as clonidine:[40] On easy, but not difficult, tasks in cognitive performance:[41] A finding taken as further support for the arousal theory discussed earlier (i.e., noise induces arousal in low aroused sleep deprived individuals to reach the optimum task arousal on easy or boring tasks).

Noise-induced stress and cognitive function in healthy adults

Human cognitive performance encompasses many domains, such as attention, short- and long-term memory, decision-making, and executive control processes. The same domain may be affected to a varying degree by different types of noise stressors.[4] For example, recall and recognition are more impaired by meaningful irrelevant speech compared to traffic noise.[4] In addition, the same type of noise stressor may impair one cognitive domain, while having no effect on another.

A search through the PubMed, Scopus, and Web of Science was conducted to identify published, peer reviewed articles in English comprising an experimental investigation of acute noise on cognition. Inclusion criteria were as follows: Study focused on environmental (aircraft, traffic, and social stimuli) or white noise, encompassed stimuli loud enough to cause moderate annoyance (>50 dB) according to WHO[10] guidelines, comprised a non clinical human adult (18-64) population, and specified a measurable cognitive task. The search was conducted using a combination of the key words "noise" or "NS" or "auditory distraction" and "cognition" or "memory" or "attention" or "impairment". The initial searches uncovered 346 relevant studies, which were then examined by hand to check they met inclusion requirements. References of selected papers were inspected for additional relevant articles.

A total of 31 studies were included in the review [Table 1] summarized in the next sections, classified by cognitive domains of attention, executive function and memory. These domains are particularly important in the context of schizophrenia.[42] It is appreciated that a clear distinction between cognitive processes in these tasks is not always possible; where processes overlap or tasks used in studies span several domains, this is acknowledged.

Noise stress and attention

The term "attention", as with most cognitive function constructs, does not refer to one process but several different processes (i.e., bottom-up and top-down[64]). Here, we specifically consider noise effects on top-down attention in vigilance tasks, such as the continuous performance task. Vigilance tasks assess sustained attention[22,62,63] and require participants to make a prespecified response to target stimuli, which appear among distracter stimuli at unpredictable times.

As is evident from the findings presented in Table 1, the effect of noise on attention is dependent on task complexity. For example, under loud noise Jerison[62] found no effect of noise on a simple vigilance task (a modified "Mackworth Clock Test"); while Hockey[22] on the other hand, observed a noise effect during a more complex multi-source monitoring vigilance task. Hockey's demonstration that NS can cause

Table 1: Studies (presented in reverse chronological order) investigating the effect of noise on cognitive performance in healthy adults

References	Participants	Noise characteristics	Study design	Variables examined	Findings
Reynolds *et al*.[43]	70 healthy adults (26 men, 44 women). Age range: 16-18	Silent condition versus continuous noise (70 dB): Environmental noise and contemporary music	Between subjects	Abstract reasoning, mental arithmetic, IQ, personality	Abstract reasoning better under silence compared to both noise conditions. A weak negative correlation between neuroticism and performance in music and a strong negative correlation in environmental noise
Perham *et al*.[44]	36 healthy adults (gender not specified). Age range: 18-30	Silent condition versus continuous noise (65 dB(A)-75 dB(A)): Office noise with speech and office noise without speech	Within subject	Serial recall, mental arithmetic	Both noise stimuli impaired serial recall and mental arithmetic
Alimohammadi *et al*.[45]	90 healthy adults (54 men, 36 women). Age mean (SD): 23.46 (1.97)	Silent condition versus continuous low frequency noise: Quiet (50 dB) and loud (70 dB)	Within subject	Executive function (Stroop), attention, personality, noise annoyance	Attention accuracy increased and RTs for Stroop and attention increased under both noise conditions
Tsuchida *et al*.[46]	52 healthy adults (31 men, 21 women). Age range: 18-33	Intermittent noise: A pure 500 Hz tone and 48 environmental noise (80 dB)	Between subjects	Selective attention	Selective attention RTs increased during environmental noise
Jahncke[47]	24 healthy adults (16 men, 8 women). Age mean (SD): 25 (SD not specified)	Continuous noise: Quiet (30 dB(A)) versus irrelevant speech (51 dB(A))	Within subject	Memory (semantic and episodic; long and short-term), selective attention, mental arithmetic	Selective attention and episodic short-term memory tasks more sensitive to noise disruption
Szalma and Hancock[1]	242 healthy adults (gender not specified). Age not specified	Continuous versus intermittent: Speech noise, non-speech noise, music, mixed speech/non-speech: Short, long noise duration (median split at 1.1 min)	Meta-analysis	191 studies assessing accuracy or speed of response on a range of perception, cognitive and psychomotor tasks (no further specific details)	Speech stimuli more disruptive to cognitive performance than non-speech, mixed speech/non-speech and music. Intermittent noise more disruptive than continuous noise
Smith *et al*.[48]	34 healthy adults (11 men, 25 women). Age range: 18-25	Continuous noise via headphones: Office noise (65 dB)	Within subject	Mental arithmetic	Mental arithmetic performance initially disrupted by office noise but improved after habituation of 10 min
Cassidy and MacDonald[49]	40 healthy adults (gender not specified). Age range: 14-50	Silent control versus continuous noise (60 dB); music with high negative or low arousal potential, and everyday noise	Between subjects	Recall (immediate, free, numerical, delayed) and executive function (Stroop), personality	High arousal music and everyday noise, compared to low arousal and silence, impaired immediate and delayed recall. Free recall and Stroop better in silence (high arousal < everyday noise < low arousal). Stroop performance for introverts < extraverts in high arousal and everyday noise
Chiovenda *et al*.[50]	71 healthy adults (49 men, 31 women). Age mean (SD): 42.80 (7.25)	Continuous noise: Traffic (90 dB)	Between subjects	ERPs, tactile P300 during auditory oddball, attention, anxiety, occupation (office, traffic worker)	Noise exposed participants demonstrated a wider P300 amplitude in nonstress and traffic noise conditions as well as higher sensitivity to noise during traffic noise exposure
Hillier *et al*.[12]	32 healthy adults (16 men, 16 women). Age mean: (SD) 25.08 (8.34)	Silent control condition versus continuous noise: White noise (90 dB)	Within subject	Verbal and visuospatial memory, cognitive flexibility (compound remote association task)	Noise increased RT and reduced the number of correct cognitive flexibility responses
Boman *et al*.[4]	288 healthy adults (approx 135 men, 153 women). Age range: 13-65	Quiet control condition (38 dB) versus continuous noise (66 dB): Irrelevant speech, and traffic	Between subjects	Episodic and semantic memory, age	Noise more disruptive to episodic compared to semantic memory. Comprehension, cued recall and recognition more impaired by meaningful irrelevant speech compared to traffic noise
Gisselgård *et al*.[51]	14 healthy adults (men only). Age range: 20-37	Continuous noise played via headphones (65 dB): Irrelevant speech, white noise	Within subject	Serial recall, working memory load, positron emission tomography measurement of rCBF	Irrelevant speech increased rCBF in bilateral superior temporal regions and in the right borderline to the middle temporal cortex
Chajut and Algom[52]	20 healthy adults (Exp 2, gender not specified). Age range: 20-25	Continuous noise: Loud (84 dB) and quiet (55 dB)	Within subject	Executive function, (Stroop and Garner interference)	Loud, compared to quiet, noise diminished Stroop and Garner effects (reduced interference)

Table 1: (Continued)

References	Participants	Noise characteristics	Study design	Variables examined	Findings
Hygge *et al*.[14]	96 healthy adults (48 men, 48 women). Age range: 18-20	Quiet control condition (38 dBA Leq) versus continuous noise (66 dBa with 78 dBA peak): Traffic, irrelevant speech	Between subjects	Attention, episodic and semantic memory	Recall of text, retrieval from semantic memory and attention impaired to the same degree by the different types of noise
Ballard[53]	155 healthy adults (19 men, 136 women). Age mean (SD): 19.98 (2.12)	Intermittent noise: Quiet (~30 dB) and loud (~ 90 dB)	Within subject	Attention three versions of the continuous performance task (response inhibition and traditional [fast and slow]), anxiety	Low-anxious, compared to high-anxious, participants had more omissions in the traditional task under quiet conditions and less under loud conditions; and fewer response inhibition commissions in quiet, compared to loud conditions
Onate *et al*.[54]	62 healthy adults (39 men, 23 women). Age mean (SD):19.55 (1.25)	Quiet control noise versus continuous noise; uncontrolled athletics track sideline (average sound level not specified)	Within subject	Attention, executive function (Stroop), recall, reaction time, problem solving (trail making A and B)	No difference between performance in the controlled and uncontrolled environments. A practice learning effect found for all tasks
Ellermeier and Zimmer[18]	72 healthy adults (31 men, 41 women). Age range: 19-44	Quiet condition (40 dB) versus continuous noise (76 dB) played through headphones: Foreign speech versus pink noise	Within subject	Serial recall, noise sensitivity	More errors under foreign noise compared to both pink and no noise. High noise-sensitive individuals made more errors in all conditions compared to low-sensitive individuals
Jones and Macken[55]	116 healthy adults (47 men, 69 women). Age not specified	Intermittent noise (65 dBA); pitches of syllables and tones	Within subject	Serial recall of visual material	Tones produced an equivalent effect as speech. Effect of noise not on encoding but during storage of the serial lists
Jelínková *et al*.[17]	101 healthy adults (gender and age not specified)	Continuous noise (75 dBA); traffic	Field study	Attention, noise sensitivity, IQ	Noise sensitive individuals had reduced mental ability and attention during traffic noise
Gulian and Thomas[31]	72 healthy adults (36 men, 36 women). Age range: 19-30	Continuous white noise: Loud (85 dB) versus (50 dB)	Between subjects	Mental arithmetic, gender, cognitive set (neutral, positive, or negative instructions)	Noise had a detrimental effect on speed (but no effect on accuracy). Loud noise (85 dB) affected processing speed for women, but not men. In quiet conditions women faster than men under neutral and positive cognitive sets
Smith and Broadbent[56]	137 healthy adults (women only). Age not specified	Continuous free field noise: Loud (85 dBA) versus quiet (55 dBA)	Between subjects	Executive function (Stroop), noise duration	Participants tested in quiet after 30 min of noise exposure relatively quicker at naming colors, but slower at reading color names, compared to when they had not been exposed to any noise
Nurmi and von Wright[57]	72 healthy adolescents (gender not specified). Age range: 16-18	Intermittent white noise and silence	Between subjects	Immediate and delayed recall, personality	Noise during learning decreased recall in neurotic individuals and high-anxious individuals. Conversely, it improved recall in stable non-anxious individuals. Noise during recall only affected complex tasks
Salamé and Baddeley[58]	92 healthy adults (28 men, 64 women). Age mean (SD): 28.6 (SD not specified)	Quiet condition (37 dB) versus intermittent noise (75 dB); nonsense or meaningful words	Within subject	Immediate memory for visually presented digits	Unattended speech impaired immediate memory. Disruption to memory similar for nonsense and meaningful words. Articulation suppression prevents the irrelevant speech effect
Colle and Welsh[59]	72 healthy adults (20 men, 52 women). Age not specified	Continuous noise (85 dB) played via headphones; foreign speech	Between subjects	Immediate and delayed recall with visual presentation and written recall	Irrelevant foreign language impaired performance on phonologically different, but not similar, lists. The noise effect eliminated after 30 s of mental arithmetic
Hartley and Adams[3]	50 healthy adults (men only). Age not specified	Continuous noise (sound level not specified)	Within subject	Executive function (color-word Stroop), noise duration	Brief noise exposure beneficial to performance (causing reduced interference). Loud noise impaired performance causing increased interference

(*Continued*)

Table 1: (Continued)

References	Participants	Noise characteristics	Study design	Variables examined	Findings
Glass *et al*.[60]	49 healthy adults (men only). Age range: 17-24	Intermittent noise (110 dB)	Between subjects	Attention (proof reading task), perceived noise controllability, skin resistance	Adaptation to uncontrollable noise increased tonic skin conductance and impaired performance after the termination of the noise
O'Malley and Poplawsky[61]	74 healthy adults (44 men, 30 women). Age not specified	Silent condition versus intermittent white noise (75 dB, 85 dB, 100 dB)	Between subjects	Attention, executive function (Stroop)	Noise impaired attention (reduction in the number of peripheral words recalled). Less Stroop interference in the noise condition
Hockey[22]	12 healthy adults (men only). Age range: 17-25	Continuous conditions: Loud (100 dB) and quiet (70 dB)	Within subject	Attention	Noise exposure resulted in participants attending to high priority information
Hockey and Hamilton[2]	68 healthy adults (gender not specified). Age not specified	Continuous noise: Quiet (55 dB) and loud (80 dB)	Between subjects	Short term memory with an irrelevant cue (word location)	Participants attended more to high importance information at the expense of less important information in the loud noise condition
Jerison[62]	37 healthy adults (men only). Age not specified	Continuous noise: Loud (110 dB) and quiet (77.5-88.3 dB)	Within subject	Vigilance	Noise impaired signal detection performance after 1.5 h of testing
Jerison[63]	20 healthy adults (men only). Age not specified	Continuous noise: Loud (112.5 dB) and quiet (79 dB) white noise	Within subject	Vigilance (Mackworth clock task)	No effects of noise

RTs = Reaction time, IQ = Intelligence quotient, rCBF = Regional cerebral blood flow, ERP = Event related potential, SD = Standard deviation

attention to switch from being labile to focusing on central aspects of the task has been replicated using different tasks and noise sources.[52,53] The finding of reduced interference from the task irrelevant stimuli [the word in the color naming condition of Stroop][52] supports the postulate that noise stressors compete for attentional resources,[65] thus impairing performance that relies on peripheral information. This explains why NS can both improve and impair task performance; central aspects of the task would be improved at the expense of peripheral cues.

The above findings are in keeping with the attention depletion hypothesis,[66] which predicts that individuals should have more attentional resources when stress is low compared to when stress is high, thus implying a negative relationship between NS and cognitive performance for attention demanding tasks but no relationship for simple nonstressing tasks. Furthermore, individual differences moderate an individual's reaction to noise stressors. For example, noise-induced impairment in the continuous performance tasks is only present in high-anxious individuals.[53] This supports the earlier discussion regarding the interactive effects of external environmental factors and internal predispositions in cognitive performance.

Noise stress and memory

Memory is defined as the process of "information acquisition, storage and retrieval" (p. 324).[67] There are several dichotomies of memory (i.e., explicit and implicit, short and long-term, semantic and episodic). The literature so far has largely focused on the effects of NS on episodic and semantic long- and short-term memory. A discussion of noise effects on short-term memory will be discussed later in the executive function section. Episodic memory relates to the capacity to re-experience events in the context they originally occurred in. Semantic memory is concerned with long-term memory of facts and concepts unrelated to personal experience.[68]

Different types of realistic (acute) noisy conditions (i.e., irrelevant speech, aircraft and road traffic noise) have been shown to have a negative effect on both episodic and semantic memory.[14,69] However, not all studies show significant disruption.[70] The disparity of results could be attributed to the inconsistency of stimuli used across studies, or could be explained in line with the attention-depletion hypothesis;[66] namely, noise improves memory for central aspects of the tasks at the expense of secondary features of the task. Disparities in the literature could also be in part attributed to a failure to separate the effects of NS on the encoding and retrieval stages of memory. To explore this possibility, Hygge *et al*.[14] used a procedure that enabled the delineation of the encoding and retrieval phases for episodic memory tasks by separating them in time, and demonstrated that noise effects were restricted to episodic recall and retrieval from semantic memory, with similar disruption by the speech and non-speech stimuli.

A few studies have examined distinct effects of noise with and without a social component (i.e., irrelevant speech versus traffic noise) and report disruption of the semantic memory networks to the same degree both types of noise stimuli.[4,14] However, tasks used in such studies are not free from episodic memory (as participants must remember words associated with the experimental context) so we cannot decipher whether noise exerts its effect purely on the semantic network. In semantic fluency, a true semantic task as the list is generated internally,[71] meaningful speech impairs performance to a greater degree than meaningless speech. The disparity of results regarding the influence of the type of noise stimuli on memory systems illustrates the importance in delineating noise effects for episodic and semantic memory, the different stages of memory (recall and retrieval), and different types of stimuli (i.e., speech versus non-speech social stimuli vs. traffic).

Noise stress and executive function

Executive function is the term describing functions involved in carrying out goal-directed behavior. Psychometric assessments of executive function include tests of divided attention, working memory (WM), mental flexibility, and inhibition of pre-potent responses. WM refers to the dynamic short term storage and manipulation of information. Mental flexibility is important for carrying out complex tasks and switching between jobs. Inhibition of pre-potent response is important in situations when our automatic responses are not correct and need to be suppressed.

This section will focus on WM, mental flexibility and inhibition of pre-potent response. Divided attention has already been covered under the "noise stress and attention" section.

Noise stress and working memory

Working memory is a system that allows the simultaneous storage and manipulation of information held in the short-term memory store.[30] A number of cognitive tasks involve WM, including reasoning and language comprehension tasks.[72,73] However, cognitive tasks commonly used to assess WM often suffer from lack of domain specificity. More specifically, WM is associated with both memory and executive functions, as indicated by its involvement in retaining information to be held in short-term memory for use in problem solving. WM is known to be affected by daily stressors.[66] Furthermore, it has recently been proposed that WM controls the effect of NS on selective attention.[46] The detrimental effects of noise on WM task involving high load were appreciated in the WHO[10] report.

Noise operating on a wide range of frequencies (i.e., broadband noise) has been shown to have a distracting effect on short-term memory for visual-verbal and visuospatial items.[58,74] The finding that unattended speech impairs WM led to the proposal that noise stressors impair WM by disrupting participants' ability to rehearse material using their phonological loop the verbal storage component of WM.[75,76] Support for this theory comes from neuroimaging studies showing that brain areas involved in verbal WM are suppressed, while participants inhibit irrelevant speech in order to maintain WM.[51,77] The functional brain correlate of the irrelevant speech effect is dorsolateral prefrontal cortex (PFC) activity; a finding attributed to the idea that the ability to suppress distractions is sub-served by the central executive, which is responsible for encoding, storage and retrieval of short-term memory in Baddeley's[72] WM model. This component is a multi-dimensional construct as it incorporates memory, attention and executive processes, allowing the attentional control and manipulation of information retained in the phonological loop and visual-spatial sketch pad. The multi-dimensional nature of WM highlights the necessity to consider this domain as a possible confound when interpreting attention and memory findings.

Noise stress and mental flexibility and inhibition of pre-potent response

Mental flexibility and inhibition of pre-potent response both involve inhibition of response (in that to set-shift successfully you must stop responding to one instruction and switch to another). In one study, low cognitive load tasks involving set shifting (such as trail making part B) were not significantly disrupted by environmental distraction that included social noise.[54]

The Stroop task is a much more complex task that measures inhibition of pre-potent response along with selective attention and processing speed and is seen as a "general indicator of cognitive flexibility and control" [p. 231, 50]. Some studies report less interference (reduced cognitive inhibition) as a result of noise,[3,61] while others find no effect.[56] This inconsistency may be partly due to the varied duration and characteristics of the noise used. For example, unpredictable acute loud noise has been shown to increase interference in incongruent conditions during long exposure to noise, but not during brief exposure.[3,78] Further support for the detrimental effects of long-term exposure on Stroop performance comes from a study which showed longer executive times in the color-name Stroop task in long-term noise exposed traffic police officers, compared to control office workers.[50] In addition to the duration of noise, the content of noise is also important as suggested by the finding that high affect music and everyday noise are significantly more detrimental to Stroop performance compared with silent and low affect music conditions.[49]

Summary and critical evaluation of current evidence

Overall, there is a clear adverse effect of continuous environmental noise[1,4,14,17,46] on attending to peripheral cues, WM, and episodic recall in non clinical adult participants. However, the findings are rather inconsistent in some other domains. There may be a number of reasons for this.

First, most studies have ignored individual differences, such as personality, that independently relate to NS and also interact with task parameters. Second, studies have used noise stimuli with inconsistent classification of noise on duration, loudness (e.g., Belojevic *et al*.[29] define low noise as <55 dB and high noise as >65 dB; while Hockey[22] defined low noise as 70 dB and high noise as 100 dB), predictability and content dimensions. Studies that use a nonrealistic noise stressor (e.g.,[12] used continuous white noise of 90 dB) rather than more environmental realistic stimuli cannot be generalized to realistic situations. Third, many studies have used between - subject designs. Within-subject variability in performance is important to avoid falling into the "ecological fallacy" of assuming patterns between groups also occur at the individual level.[79] It is clear that different groups of people will respond differently to similar stress levels and it is important to carry out within-subject analysis to understand between — group differences. Finally, the studies have used varied task designs. For example,[12] used a modified version of the Hopkins Verbal Learning Test[80] with stimuli presented visually rather than verbally. The visual presentation of this task may have masked any effect that would normally been found in this task had the stimuli been presented verbally.

Cognitive impairment under noise stress: Exacerbation in schizophrenia?

Schizophrenia is characterized by psychotic symptoms, motivational impairment, affective dysregulation and alterations in information processing.[8,81] It is also known to be associated with environmental stressors so will be used in this paper as a reference to explore possible NS effects in clinical populations. There are a number of reasons to suspect that NS may have even stronger adverse effects in schizophrenia than that seen in healthy groups.

First, schizophrenia is a heterogeneous disorder characterized by aberrant functional and cognitive processing in the face of stressors, be they interpersonal (i.e., social interaction or work demands), biological (i.e., maternal viruses or neurological insult), or environmental (i.e., urbanization).[82] These stressors are believed to interact with internal dispositions to increase the risk of developing the disorder. The incidence of schizophrenia in city dwellers is double that of those brought up in rural areas.[83] This is largely attributed to the heightened stress potential of the social environment in cities.[84,85] However, it is already established that schizophrenia patients have problems ignoring unwanted noises in the environment,[86] perhaps at least in part mediated by their known sensory gating impairments, indexed for example, as impaired pre-pulse inhibition of the startle response.[87,88] Although, as yet, there is no direct literature on noise sensitivity in schizophrenia, on the basis of a study showing increased hemodynamic response to urban noise,[86] one could postulate that individuals diagnosed with schizophrenia would be more noise sensitive than non clinical individuals, and this would be reflected also as exaggerated NS-induced disruption of their cognitive performance.

The individual difference literature is a second line of evidence that points to a heightened detrimental effect of NS in schizophrenia, and other psychiatric disorders such as depression and post-traumatic stress disorder. Myin-Germeys and van Os[89] posit that sensitivity to stress can be assessed by measuring affect. Higher levels of anxiety and depression are found in schizophrenia[90,91] and are associated with the severity of positive symptoms.[92] Anxiety and depression also increase the risk of developing schizophrenia[93,94] and overlaps with aspects of schizotypy.[95] Another individual difference variable pointing to exaggerated impact of noise in schizophrenia populations is IQ. People diagnosed with schizophrenia, on average, are known to have lower current IQ than healthy people[96] and there is a substantial genetic overlap between schizophrenia and IQ.[97] Furthermore, higher IQ is reported to be a protective factor against schizophrenia.[98] Lower IQ and higher variation of within-subject trial-to trial cognitive performance may be indicative of effects of "degraded neural processing efficacy"[99] and as mentioned earlier would be expected to result in greater disruption under noise in lower IQ schizophrenia groups.

A third route by which patients diagnosed with psychiatric disorders may be more impaired by noise, compared to their healthy counterparts, is as a result of their symptom levels. Indeed urban NS has been shown to increase paranoia and depression levels in psychosis.[100] In accordance with the high experience of paranoia in psychotic populations, and the association of paranoia (e.g. perceived threat from others) with social situations,[101] social noise may be more disruptive to cognitive and affective indices compared with neutral noise (i.e., building site noise). Furthermore, the well-documented heightened stresses of the social environment for patients[84,85] could add to the preferential disruption to this patient group by social noise stimuli. Another symptom, which may moderate noise effects is sleep disturbance. It is a well-documented symptom and often precedes the appearance of other symptoms in psychosis.[102] Insomnia is associated with paranoia even in the general population[103] which, as already mentioned, would be expected to increase sensitivity to social noise.

Fourth, neurotransmitter systems, already found to be dysfunctional in schizophrenia, are thought to be involved in noise-induced stress. Mild NS preferentially increases dopamine turnover in the PFC of monkeys.[104] Dopamine blocking drugs (haloperidol, SCH 23390) and drugs that reduce PFC dopamine turnover (clonidine, naloxone hydrochloride) ameliorate NS-induced deficits in delayed-response performance in monkeys,[104] pointing further to NS exerting its effect through hyperdopaminergic mechanisms taking the PFC "offline" to allow more habitual responses mediated by posterior cortical and sub-cortical structures to regulate behavior. Based on this research in monkeys, and known abnormalities in dopaminergic and other relevant neurotransmitter systems in schizophrenia, it seems reasonable to suggest that NS would be particularly disruptive to cognitive processes sub-served by the frontal cortices (e.g., WM) in this population.

Finally, not only may there be an exaggerated effect of NS on cognition in schizophrenia, it may be particularly evident on certain domains in combination with pre-existing impairment commonly found in this population. For example, verbal memory deficits in schizophrenia are reliably present and attributed to impaired recall rather than recognition.[105-107] This profile of deficits mirrors the detrimental effect of NS on recall, but not recognition in healthy participants.[14,58] WM is another cognitive domain that is known to be independently disrupted by both NS [Table 1] and psychosis.[108]

Conclusions and directions for future research

Based on the evidence available so far, we conclude that environmental NS exerts a negative effect on certain cognitive functions, namely, attention, WM and episodic recall. This conclusion, however, is based on a number of studies which are not unified in terms of noise stimuli (content, loudness, frequency, and duration), cognitive domain/task of interest, and sample characteristics assessed. As discussed earlier, current studies do not allow a precise evaluation in terms of which cognitive domains may be particularly sensitive to noise and to which type of noise (e.g. speech vs. non-speech). We make a number of recommendations to overcome the limitations outlined previously and significantly advance this field.

First, all noise studies should assess NS-induced deficits against baseline "no noise condition" performance, with baseline performance considered as a confound in accordance with the finding that lower IQ may be indicative of effects of "degraded neural processing efficacy".[99]

Second, studies should strive to use a repeated - measure design with a large enough sample size to allow investigation of a battery of cognitive tasks. Such a design would allow investigation into whether NS effect is particularly strong for some, relative to other, cognitive domains. Similarly, studying different types of environmental noise stimuli (i.e., speech versus non-speech) in the same study will provide within - subject data as to which type of noise stressor is most detrimental to which domain.

Third, relevant individual differences variables need to be considered in order to reduce apparent "error" variance within studies and increase comparability between them. This review shows a clear interaction between individual differences (e.g., personality) and the impact of NS on performance.

Fourth, more consistency is needed in the literature concerning the characteristics of noise stimuli used (i.e., what constitutes a loud noise). To allow consistency between studies, sound levels could be chosen in accordance with the WHO guidelines [Appendix 1].[10] For example noise levels could be classified as "low" at the level of speech (30 dB), "moderate" at the level that caused moderate annoyance (50-55 dB) and "loud" at the sound level experienced industrial, commercial, shopping and traffic areas (>70 dB). A unified classification of noise (in terms of duration, loudness predictability and content dimensions) would allow easier interpretation of the NS literature. Social and non-social categorization would be particularly meaningful bearing in mind its potential impact on clinical populations.

Fifth, once the profile of deficits caused by specific noise stressors has been determined, future studies could explore the reversibility of any noise-induced cognitive impairment. There is some evidence that, for memory at least, impairment by chronic noise exposure is reversible following noise reduction measures.[109] However, the literature at present is sparse on the reversibility of noise-induced impairment in other domains.

Finally, future studies should investigate the impact of noise in clinical populations following the recommendations outlined above. Studies which draw conclusions on the influence of a particular variable on patients' cognition in relation to a non-pathological group are helpful in delineating group level deficits, but do not allow conclusions to be drawn concerning intraindividual processes that occur as a result of stressors. Schizophrenia is recommended as a target group as many of the processes impaired by NS are also independently affected by psychosis and there is a well-known link between psychosis and high stress reactivity.[89] Given the association between cognitive impairment and poor functional outcome in schizophrenia,[7] it is important for future studies to elucidate any factors, such as NS, that may exacerbate cognitive dysfunction in schizophrenia. The investigation of whether noise pollution causes further deterioration in patients' cognitive level in real life settings, and if it does, whether it may interact with other risk factors for schizophrenia, will have implications for methodologies of future clinical and pharmacological studies focusing on cognitive improvements in schizophrenia.

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How to cite this article: Wright B, Peters E, Ettinger U, Kuipers E, Kumari V. Understanding noise stress-induced cognitive impairment in healthy adults and its implications for schizophrenia. Noise Health 2014;16:166-76.

Source of Support: Funded by Medical Research Council, UK and Institute of Psychiatry, KCL. **Conflict of Interest:** None declared.