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Understanding susceptibility to inattentional deafness in safety–critical environments

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ABSTRACT

Introduction: Dynamic occupational environments, such as construction sites, present workers with frequent changes, some of which pose serious risk. Workers are expected to detect and respond to these changes using sensory cues, including auditory warnings intentionally designed to draw attention to hazardous conditions. However, these cues often compete with high cognitive load, which can result in missed warning sounds, a phenomenon known as inattentional deafness. This study examines susceptibility to inattentional deafness during a simulated construction task. *Method:* Data were collected from 136 participants, including 72 individuals and 64 participants who worked in 32 pairs. All participants completed a mechanical–electrical assembly in a controlled laboratory environment with continuous construction noise. Before the task, participants received a brief pre-job-style briefing instructing them to stop work and move to a designated safety zone upon hearing any sound that could indicate hazardous energy. During the task, participants were randomly assigned to hear either an Air Horn or a Hissing cue and to work individually or collaboratively. Each participant (or pair) received three successive bursts of the assigned cue at 81, 83, and 85 dB presented at random intervals. *Results:* Overall detection was 62%, with individuals detecting 58%, while pairs detected 71%. Sound type was the strongest determinant of noticeability, as the Air Horn was detected significantly more often than the Hissing cue. Increasing volume produced modest improvements in detection, and pair collaboration was beneficial, although the improvement did not fully align with probabilistic expectations of redundancy. Human factors such as fatigue, emotional state, and perceived task difficulty did not significantly predict detection. *Conclusions and Practical Applications:* These findings underscore the importance of highly distinguishable auditory warnings and system-level designs that account for the inherent limitations of human attention in safety–critical work environments.

1. Background

Inattentional deafness is when an attentional load prevents an individual from detecting an auditory cue that is reasonably perceivable at the sensory level (Durantin et al., 2017). Hence, understanding susceptibility to inattentional deafness is essential for improving safety in complex, high-risk work settings. In safety–critical dynamic environments such as construction, the failure to consciously register important auditory cues can have serious consequences for worker awareness and response. Multiple crews execute interdependent tasks in temporally and spatially overlapping zones, while also interacting with specialized tools and equipment. Within such complex contexts, change is not treated as an anomaly. Rather, it is considered by many in the frontline roles to be a routine and recurring feature of work. Yet, being normalized to the notion that change is normal may not mean that workers are consistently good at noticing when it happens. In fact, decades of psychological research demonstrate that individuals frequently fail to detect alterations in their surroundings (Simons & Levin, 1997), particularly when their attention is absorbed by a primary task (Durantin et al., 2017). These attentional failures have serious

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implications for worker safety, especially in environments where hazards are signaled not only visually but also through sound, since auditory cues, such as alarms, backup beepers, or shouted warnings, can be easily masked or ignored amid the noise and cognitive load of construction work.

Construction sites are not only visually complex but also acoustically intense, with sound levels frequently exceeding 85 dB. For context, this is about as loud as a blender or heavy city traffic, and prolonged exposure at this level can cause long-term hearing damage (Suter, 2002). Beyond these risks, exposure to such noise levels on a regular basis can make it challenging for workers to maintain their situational awareness. In these conditions, critical auditory cues that signal danger may be masked by environmental noise or overlooked entirely. This difficulty is likely intensified by the cognitive demands of construction tasks and a complex work environment, which would reasonably consume most, if not all, of a worker's attentional capacity. As a result, it is possible that audible sounds that pose a significant risk may not reach conscious awareness. Because many of these auditory signals may develop as work progresses over a given day (i.e., they are last-minute or task-level changes) that require rapid recognition and decision-making, assuming workers can reliably detect and respond to such changes may overlook important cognitive constraints, especially under high workload and noise conditions.

The present study investigates inattentional deafness in construction by testing whether novice workers can detect safety–critical sounds while engaged in a construction task. To address this, we designed a controlled simulation that introduced auditory signals representing hazardous energy at randomized intervals during task performance. This design allows systematic evaluation of detection performance under different conditions. This present research asks four central questions: Research Question 1: To what extent are workers susceptible to inattentional deafness while completing construction tasks? Research Question 2: Does detection performance differ when individuals work alone compared to in pairs? Research Question 3: How do the characteristics of the auditory signals, including type and volume, influence noticeability? Research Question 4: How are detection outcomes associated with individual human factors such as fatigue, emotions, Attention-deficit/hyperactivity disorder (ADHD) symptoms, and perceived task difficulty? By examining these questions, this research work advances understanding of how cognitive limitations interact with the demands of construction work and informs the design of safety interventions that reflect the realities of auditory perception on jobsites. While this experiment centers on construction, the cognitive mechanisms it addresses extend to many safety–critical environments where auditory signals serve as early warnings. By framing construction as one instance of a broader class of attention-intensive work settings, the study contributes to understanding the general conditions under which workers fail to notice critical cues.

This work focuses on inattentional deafness, which is defined as the phenomenon in which individuals fail to detect an auditory cue that is reasonably perceivable at the sensory level for human beings due to attentional load (Durantin et al., 2017). Unlike hearing loss, which is a physiological limitation, or change deafness, which occurs when a person fails to notice that an ongoing sound has changed (e.g., one sound being replaced by another; Callan et al., 2018), inattentional deafness refers to the failure to detect an otherwise audible sound because attentional resources are consumed by other tasks (Dehais et al., 2019; Macdonald & Lavie, 2011). Consider the following examples of inattentional deafness:

Pilots who fail to detect critical cockpit alarms under conditions where their attentional resources are narrowed (Dehais et al., 2014)
Drivers under high perceptual load have reduced situational awareness, which could lead to failure to perceive auditory alerts (Van Der Heiden et al., 2022)
Participants missing an auditory cue while being focused on a visual task in the laboratory (Macdonald & Lavie, 2011)

This lack of auditory awareness can be especially concerning in dynamic work settings, where the ability to register and interpret changes in one's environment is essential for hazard recognition and timely response. Although inattentional deafness has been studied in domains such as music perception, aviation, and controlled laboratory experiments, it has not been systematically investigated within construction settings (Cvach, 2012; Dehais et al., 2014; Durantin et al., 2017; Koreimann et al., 2014). Even in the psychological literature, the overwhelming focus has been on studying individuals' ability to notice and react to visual changes (Jensen et al., 2011; Rensink, 2002) only. This represents a critical gap, particularly given the construction industry's persistent challenges with fatal and severe incidents. To address this gap, the present paper reviews the literature on inattentional deafness, highlights its relevance to occupational safety, and examines the individual and contextual factors that make auditory changes harder to notice. This synthesis provides the point of departure for the study's empirical investigation in a simulated construction environment.

1.1. Foundational theories of attention

The human brain has a limited ability to analyze incoming sensory information. Several classic attention theories have provided foundational models for understanding this limitation. For instance, Broadbent (1958) proposed in the Filter Model that there is an early bottleneck, where unattended information is blocked before it can ever reach higher-level processing. By failing to reach higher-level processing, unattended information never enters conscious awareness, meaning the individual does not register the stimulus at all. This model emphasizes a fixed capacity system that filters information based on physical properties, like sound pitch or location. Later, Treisman's (1964) Attenuation Theory introduced the idea that unattended signals are not completely discarded, but instead receive reduced processing, an idea that helps explain partial awareness of background sounds during focused tasks. Building on the above models, Kahneman (1973) introduced a more flexible framework through his Capacity and Resource Theory of Attention that suggests attentional performance depends on both task demand and the amount of available mental capacity. Expanding beyond these information processing models, Posner's (1980) Orienting Model of Attention offered a comprehensive framework linking cognitive and neural mechanisms of attention. This model explains that attention is not merely a single bottleneck but a dynamic process of shifting and maintaining focus across sensory modalities. The model further identified three key subsystems that control how attention is engaged, which are alerting, orienting, and executive control. From an occupational safety perspective, these foundational studies suggest that when task demands exceed available mental capacity, or there is a failure to orient attention effectively, workers can become highly vulnerable to missing important changes in their environment.

Modern cognitive science integrates foundational attention theories with neurobiological insights to explain these attentional failures in dynamic environments. Wickens (2008) proposed that attentional resources are organized across multiple pools based on processing stage, perceptual modality, visual channel, and processing code. As a result, engaging in a demanding visual task may impair auditory processing not due to sensory interference, but because both tasks compete for shared executive and working memory resources. Complementing this, Norman and Shallice (1986) proposed the Supervisory Attentional System, which suggests that attentional control is governed centrally and adjusts dynamically based on task demands. This system can prioritize important stimuli that would otherwise be filtered out, but when cognitive demands are excessive or attentional inertia develops, even salient cues may fail to trigger conscious awareness.

Together, these perspectives highlight that auditory detection is

shaped not only by hearing acuity but also by the allocation of limited attentional resources. Table 1 summarizes how these mechanisms undermine the assumption that frontline workers can reliably detect change across sensory modalities. Construction jobsites, especially, are acoustically complex environments where high background noise and competing auditory signals create substantial challenges for effective sound recognition.

1.2. Beyond attention in understanding inattentional deafness

Although attentional theories highlight cognitive limits, neurophysiological evidence shows how these limits are instantiated in the brain during inattentional deafness. Recent neurophysiological studies provide converging evidence that inattentional deafness extends beyond self-reported missed auditory cues and is reflected in measurable disruptions of auditory processing at the neural level. Using magnetoencephalography, Molloy et al. (2015) demonstrated that high visual perceptual load suppresses early auditory-evoked activity in regions such as the superior temporal sulcus, along with later attenuation of the P3 component, which is typically linked to conscious stimulus evaluation. Similarly, Dehais et al. (2019) and Giraudet et al. (2014) found that missed auditory alarms during flight simulation tasks were associated with diminished amplitudes in early ERP components (N100, P3a, and P3b), indicating a breakdown in both perceptual encoding and attentional redirection. Building on this, Durantin et al. (2017) used fMRI and EEG to show that during missed alarms, the right inferior frontal gyrus, a region implicated in executive inhibition, exhibited increased activity and suppressive coupling with the auditory cortex. These findings suggest that the brain may not simply fail due to limited capacity but instead may strategically inhibit sensory input to prioritize performance on the primary task.

Table 1
Foundational Theories of Attention and Relevance to Inattentional Deafness.

Theory Name (Key Proponent, Year)	Core Principle	Primary Mechanism Leading to Inattentional Deafness
Filter Theory(Broadbent, 1958)	Early, all-or-none filtering of stimuli based on physical characteristics before semantic processing.	Unattended auditory stimulus not selected by the filter due to its physical properties, leading to no further processing or conscious awareness.
Attenuation Theory (Treisman, 1964)	Unattended stimuli are attenuated (weakened), not fully blocked; meaningful or salient stimuli can pass the attenuator.	Auditory stimulus is attenuated; if its signal strength (post-attenuation) plus its relevance/salience doesn't cross a threshold, it's not consciously perceived.
Capacity Model (Kahneman, 1973)	Attention is a single, limited pool of mental effort/ resources that can be flexibly allocated.	Primary task consumes most available attentional capacity, leaving insufficient resources for processing a concurrent auditory stimulus.
Orienting Model (Posner, 1980)	Attention operates through three interrelated subsystems, alerting, orienting, and executive control, that govern how attention is engaged, directed and maintained across sensory modalities	Ineffective engagement or orienting of attention toward auditory cues, due to high visual load, reduced alertness, or failure of executive control, hinders the timely detection and processing of relevant auditory cues.
Multiple Resource Theory (Wickens, 2008)	Attention comprises multiple, independent resource pools (modalities, stages, codes). Interference occurs when tasks share the same pools.	High load on visual or other non-auditory resources that share processing stages or codes with auditory processing depletes resources needed for the auditory stimulus.
Load Theory (Lavie, 1995; Lavie et al., 2004)	Distinguishes perceptual load (affecting stimulus perception) and cognitive load (affecting control over perceived stimuli via working memory).	High Perceptual Load: Auditory stimulus not perceived due to exhausted perceptual capacity. Low Perceptual/ High Cognitive Load: Auditory stimulus may be perceived but cognitive control fails to prioritize/ respond due to WM overload.
Supervisory Attentional System (SAS) (Norman and Shallice, 1986)	A higher-level executive system controls non-routine actions, novelty, and overrides habitual responses.	SAS is overloaded by primary task demands or fails to engage for a novel/ unexpected auditory stimulus, preventing attentional shift and appropriate response.

1.2.1. Inattentional deafness in dynamic occupational environments

Although these neural studies clarify the mechanisms underlying inattentional deafness, empirical research across applied domains demonstrates how these failures manifest in practice. In controlled laboratory environments, participants often fail to detect unexpected auditory cues when their attention is directed toward visually demanding tasks, suggesting that visual load can suppress auditory awareness (Macdonald & Lavie, 2011; Molloy et al., 2015; Raveh & Lavie, 2015). This pattern is mirrored in aviation research, where pilots working under high workload conditions frequently miss critical alarms, even when they are well-trained and familiar with the task environment (Dehais et al., 2014; Giraudet et al., 2014). In driving contexts, high visual and cognitive demands reduce responsiveness to sirens or collision warnings (Murphy & Greene, 2015; Van Der Heiden et al., 2022; Zhu et al., 2025). Similar effects have been observed in healthcare, where repeated exposure to overlapping alarms can desensitize clinicians, resulting in delayed or missed responses despite the alarms being meaningful (Cvach, 2012). Music perception studies also show that narrowly focused attention can suppress awareness of salient auditory events, even in expert listeners (Batlle-Roca et al., 2024; Koreimann et al., 2009, Koreimann et al., 2014). Together, these studies demonstrate that across diverse domains, attention plays a critical role in whether auditory cues are consciously registered. These patterns have been consistently observed across domains, from lab-based attention experiments to high-stakes field environments. Table 2 synthesizes key findings across these settings to illustrate the breadth of empirical support for inattentional deafness in task-intensive contexts.

1.3. Cognitive, contextual, and individual factors shaping auditory awareness

Aside from inherent attentional constraints and neurological limitations, there are several context-relevant (e.g., individual and environment-specific) factors that can also influence the detectability of auditory changes. Some key factors that shape change detection skill, with a specific focus on auditory cues relevant to inattentional deafness, are discussed below:

1 Salience of the Change

Salience, in the context of change, refers to how much a stimulus stands out and affects what we notice or how we act; salient stimuli are the ones that naturally grab our attention or are easier for us to detect (Kayser et al., 2005). Auditory cues that are distinct, noticeable, or novel are more likely to cut through attentional barriers. A dynamic and complex environment, such as a construction site, requires that alarms are highly distinct against background construction noise and normal routine sounds.

2 Task Relevance of the Sound

Task relevance plays a significant role in whether auditory stimuli are detected under high attentional load. Studies have shown that

Table 2
Key findings from task-intensive Environments.

Context	Key Finding(s)	Citation(s)
Laboratory Studies	High visual perceptual load reduces detection of/awareness for concurrent auditory stimuli. High cognitive load can also impair responses to perceived auditory stimuli.	Macdonald and Lavie (2011); Raveh and Lavie (2015); Molloy et al. (2015); Lavie et al., (2004); Causse et al., (2016)
Aviation	Pilots under high workload (e.g., critical flight maneuvers like windshear) can fail to detect or respond to crucial auditory alarms. Pre-exposure to alarms can improve detection.	Dehais et al. (2014); Dehais et al. (2019); Giraudet et al. (2014)
Driving	High task demand (visual/ cognitive load from driving itself or secondary tasks) can compromise responses to auditory warnings like sirens or collision alerts.	Murphy & Greene, (2015); Van Der Heiden et al., (2022); Zhu et al. (2025)
Healthcare (Alarm Fatigue)	High frequency of auditory alarms, many false, leads to clinician desensitization and missed/delayed responses to critical alarms.	Cvach (2012)
Music Perception	Even trained musicians can fail to notice unexpected auditory events within music if their attention is directed to a specific musical sub-task.	Koreimann et al. (2014)

sounds that are clearly tied to task goals are more likely to capture attention. Scheer et al. (2018) found that task-relevant sounds elicited stronger brain responses even under high visual workload. However, auditory cues that conflict with the visual or cognitive demands of a task may become distractions. Hence, the auditory alert system design must be relevant and aligned with the workers' tasks at hand to ensure they are noticed within the complexity of activities on site.

3 Cognitive Load and Working Memory

An individual's working memory (WM) capacity and executive functioning are critical in determining their vulnerability to inattentional deafness. Research shows that people with lower WM capacity are more susceptible to distraction because they struggle to maintain focus on task-relevant information while inhibiting irrelevant input. De Fockert (2013) reviewed evidence that individuals with greater WM resources are better able to exert top-down control over attention, reducing the likelihood of attentional failures such as missing unexpected auditory cues under load. Similarly, experimental findings by Weast and Neiman (2010) indicate that increased cognitive load impairs the ability to selectively attend to meaningful stimuli, suggesting that executive control mechanisms become strained when WM is taxed. These studies imply that inattentional deafness is not solely a function of perceptual load but is also shaped by the availability of cognitive control resources, particularly the capacity to allocate and shift attention effectively across modalities. In this light, WM acts as a cognitive buffer that helps preserve auditory awareness even when attentional demands are high. This implies that individuals working under stress or those multitasking are likely to miss critical auditory warnings, particularly during time-pressured tasks.

4 Age and Hearing Impairment

While age and hearing loss do not directly cause inattentional deafness, they have the tendency to significantly interact with how auditory information is processed under cognitive load. Older adults tend to experience both sensory degradation and an increased cognitive effort during listening, thereby straining the attentional resources needed to detect critical sounds. Pichora-Fuller et al. (2016) discuss the increased listening effort, stress, and fatigue associated with hearing loss, which consequently can reduce one's ability to stay responsive to unexpected auditory cues. This challenge is compounded by the inconsistent use of hearing protection in noisy environments like construction sites. Suter (2002) notes that construction workers often avoid using hearing protection devices (HPD) because they believe it makes it difficult for them to hear speech and warning alarms while having them on. Hence, there is an interaction between the hearing ability, cognitive load, and the environmental noise in such a way that can increase the chances of being susceptible to inattentional deafness, especially among aging individuals or those with hearing impairments. Simply, an aging workforce and inconsistent use of hearing protection can reduce alarm detection and noticeability.

5 Fatigue

One of the conditions under which inattentional deafness occurs is cognitive fatigue alongside a high workload. Cognitive fatigue can impair auditory attention to the extent that auditory cues are missed (Dehais et al., 2019). Additionally, mental fatigue can lead to reduced attention and concentration, neglect of important information, difficulty focusing on relevant stimuli, slowed mental activity, impaired working memory, increased attentional lapses, and reduced reaction time. All these could heighten the risk of inattentional deafness in safety–critical tasks (Muñoz-La Rivera et al., 2021; Ouyang & Luo, 2024). Long shifts and demanding physical activities increase the chances of missing critical safety auditory cues.

6 Emotional State

Easterbrook's (1959) influential hypothesis posits that emotional arousal (such as stress or anxiety) leads to a narrowing of attentional focus, reducing the range of cues utilized ("tunnel vision"). This implies that under stress, peripheral cues (which an auditory alarm might be, relative to a primary visual stressor) are more likely to be missed. Shackman et al. (2011), investigating the effects of threat of bodily harm, found results partly consistent with attentional narrowing (a reduced distractor effect), but also observed a general slowing of performance, suggesting complex effects of acute threat. Other research indicates that fear, stress, and anxiety consume attentional resources, potentially reducing cognitive capacity available for information processing. Extreme emotional states can redirect cognitive resources in a way that impairs auditory awareness. Emotionally charged environments or workers experiencing job stress may likely fail to notice alarms, which could lead to delayed or no reactions.

7 Individual Differences

Personality traits and safety experience matter. These reflect non-demographic individual differences, such as personality, cognitive style, and prior exposure to safety–critical situations, that shape how workers allocate their attention. Conscientiousness, prior exposure to injuries, and proficiency in hazard recognition influence how attention is distributed (Aroke, 2022; Hasanzadeh et al., 2017). Workers with higher safety awareness and hazard identification skills tend to show more effective attention allocation, even in dynamic, complex environments.

1.4. Auditory demands in construction

Construction job sites are dynamic and multisensory environments with high visual, auditory, and cognitive demands. Suter (2002) highlights that high noise levels on construction sites can mask essential warning signals, such as back-up alarms, leading to fatalities. A noisy environment requires greater attentional effort to discern auditory cues, contributing to overall cognitive load. Furthermore, workers are required to continuously scan their surroundings while listening for machine signals, alarms, verbal warnings, and other ambient cues. Emphasizing the need for situational awareness, it has been observed that last-minute changes in construction activities have been linked to nearly 29% of fatality incidents in the United States (Lee et al., 2024). Studies by Hasanzadeh et al. (2017) and Aroke (2022) reveal that visual attention and working memory are crucial for hazard identification in construction. They demonstrated using eye-tracking devices that

cognitive overload, personality traits, and environmental stressors such as time pressure reduce situational awareness. These findings stress the importance of studying human factors in construction safety protocols. High background noise levels, frequent last-minute changes, and multitasking make designing effective alarm systems and constant training essential for injury and fatality prevention.

Importantly, inattentional deafness must be distinguished from auditory masking (when sounds are physically inaudible), hearing impairment (a sensory limitation), change deafness (missed changes in ongoing auditory streams), and alarm fatigue (learned desensitization to excessive alarms) (Callan et al., 2018; Cvach, 2012; Suter, 2002). Inattentional deafness arises when an audible signal fails to reach conscious processing due to attentional overload rather than sensory failure. It is not a reasonable expectation that frontline workers in the industry can overcome barriers impacting all humans, and therefore, the inattentional deafness context is positioned around whether changes that would otherwise be reasonably detected are missed.

1.5. Point of departure

The literature summarized above makes clear that the ability to detect auditory change is not a fixed trait but is shaped by inherent cognitive limitations, task demands, noise levels, cue characteristics, and worker experience. Although these factors are well documented across psychology and other high-risk domains, they have not been systematically tested in construction work. Unlike other occupational work settings, such as aviation or healthcare, where tasks have standard procedures and sensory cues are consistent, the construction worksite is an unusually dynamic and unstructured environment. On construction sites, work tasks evolve rapidly as crews operate in proximity, and auditory signals fluctuate unpredictably. These conditions continuously tax auditory attention, making signal detection highly context dependent. Therefore, studying inattentional deafness in this domain provides a critical opportunity to understand how attention operates in real-world, high-variability environments where sensory cues are neither consistent nor reliably engineered. This gap is consequential because construction environments combine high cognitive and visual demands with acoustically complex settings where safety often depends on rapid recognition of auditory cues. Phrases such as “keep your head on a swivel” or “stop work when something changes” are common in practice, yet they imply workers maintaining a level of awareness that is inconsistent with the evidence reviewed above. Similarly, when serious incidents are investigated, questions like “what was the person thinking?” or “how did they not see that?” are often raised, while the inherent limitations of noticeability are seldom considered. Moreover, changes are not limited to alarms, bells, and whistles; they can be subtle, such as an energized system after a lock-out tag-out has been removed, residual heat on the surface of a powered tool, a chemical leak, or a machine that is powered but jammed and no longer moving. Current safety practice frequently assumes that such cues will be noticed if they are present, yet evidence from adjacent domains challenges this assumption. Finally, even within the broader literature, evidence on inattentional deafness in high-risk industries is sparse, with most research focusing instead on failures to detect visual changes.

The present study addresses this gap through a controlled simulation of construction work designed to clarify the conditions under which auditory cues go unheard. In this simulation, participants perform a scaled assembly task while auditory signals representing hazardous energy are introduced at randomized intervals, and noticeability is systematically measured. To heighten realism, the simulated environment included a constant background noise level of 83 dB, productivity pressures, and a protocol requiring participants to stop work upon hearing hazardous sounds, instructions that were communicated during a simulated pre-job meeting. The study compares detection performance across context, auditory properties, and individual human factors. These comparisons are intended to deepen understanding of how inattentional deafness manifests in construction settings and to provide an empirical basis for improving safety training and intervention design for new/inexperienced workers. The methods, assessments, and scoping decisions, including the focus on inexperienced construction workers who are referred to as green hard hats, are described in the subsequent section.

2. Research methods

A laboratory-based construction simulation was developed to examine inattentional deafness under conditions that approximate real work settings. The research team collaborated with construction professionals from structural, mechanical, and electrical trades, each with more than five years of industry experience, to ensure ecological validity in the design of the task. The resulting testbed replicates the essential features of a typical mechanical, electrical, and plumbing (MEP) installation in a standardized environment where performance could be systematically observed and measured. To further simulate jobsite conditions, representative construction background noise was introduced, and a protocol was created that required participants to stop work when hazardous auditory cues were detected.

2.1. Experimental testbed

A typical MEP system commonly used on industrial construction sites was set up in the laboratory. This setup has a variety of scaled mechanical pipes and electrical conduits mounted on two metal pegboards with three display panels (3′ x 5′) as shown in Fig. 1. The configuration included standardized components commonly encountered on jobsites, with pipes (diameter = 2″) and conduits (diameter = 0.5″) aligned in a fixed arrangement that participants were required to assemble. Components were fabricated from polyvinyl chloride (PVC) and other lightweight construction-grade materials, selected to balance ease of



Fig. 1. Experimental setup.

handling with ecological validity. The dimensions of the panel and individual parts reflected practical constraints while still preserving the visual and physical complexity of a construction task. Task complexity was determined by the number and size of components that had to be installed on each panel by the participants. Altogether, the setup has 34 components to be installed across the three panels. Out of the three panels, the third side is the most challenging, as it requires 13 separate components, followed by the first and second panels, which have 12 and 9 components, respectively. This complexity is introduced to assess how well participants could manage intricate tasks while also monitoring their susceptibility to inattentional deafness.

Both mechanical pipes and electrical conduit configurations have 2D drawings that were drafted using AutoCAD by qualified professionals and are to be used as a guide and reference to complete the assembly task. This further strengthened the ecological validity by simulating the reliance on technical documentation that construction workers faced on the job site. Participants were not required (and informed thusly) to modify any of the pipes or conduits, either by cutting, bending, trimming, or the use of adhesives. They are to simply push and manually align each component into its designated location on the existing configuration using the provided 2D drawings. Fig. 2 shows the isometric drawings given to the participants.

2.2. Experimental procedure

The experimental procedure is shown as a flowchart in Fig. 3.

2.2.1. Background noise and auditory changes

To simulate the sensory load of an active construction site, continuous background noise was presented throughout the experiment. The noise track, which featured a mix of hammering, drilling, and machinery, was played through a wireless Bluetooth speaker at a calibrated intensity of approximately 83 dB, reflecting typical job site noise levels between 80–90 dB (Suter, 2002). Prior research has demonstrated that noise at or above 70–80 dB significantly impairs attention, reaction time, and increases fatigue (Li et al., 2021).

Superimposed on this ambient noise are two distinct auditory changes to represent the introduction of unexpected hazardous energy. The first was an Air Horn sound simulating a nearby crane lift or evacuation signal. Second was a Hissing sound simulating pressure release. Both auditory stimuli were presented at three acoustic intensities: low (81 dB), normal (83 dB), and high (85 dB). This design allowed evaluation of whether detection rates varied with acoustic salience. The two cues were intentionally selected to differ in perceptual prominence: the Air Horn being a highly salient alarm, while the Hissing represented a more subtle, task-relevant sound that could be overlooked or misattributed to other crews. By combining background construction noise with embedded hazardous cues, the procedure created a controlled yet realistic simulation in which inattentional deafness could be measured under conditions approximating real-world sensory load.

The two auditory sounds were treated as separate treatment groups. Participants were randomly assigned to either the Air Horn or Hissing condition using simple randomization, with random number generation conducted prior to data collection to produce two independent assignment lists: one for sound condition (Air Horn vs. Hissing) and one for group structure (individual vs. pair). Researchers matched incoming participants to the next available slot on each list sequentially, ensuring that neither participants nor researchers could influence group assignment. During each experimental run, the assigned sound was presented three times at random intervals, once each at low, normal, and high intensity and in that order. The fixed ordering of intensities introduces a potential ordering effect, which is acknowledged in the limitations section.

Pre-Experiment survey

Before starting the experiment, participants were asked to review the consent document in accordance with institutional review board protocols. After consent was obtained, each individual completed a baseline survey that gathered self-reported data on their key psychological and physiological indicators, such as their current emotional state, fatigue levels, and ADHD status. As noted in the literature section, these measures were collected to assist in putting the performance outcomes in context and account for known moderators of attention.

Emotional state: Positive and negative emotions were measured using the International Positive and Negative Affect Schedule Short Form (I-PANAS-SF; Thompson, 2007). This tool assesses momentary affective states and is widely used for capturing shifts in mood that can influence attentional resources.

Fatigue: Additionally, Fatigue was assessed with the Positive and Negative Affect Schedule (PANAS) Fatigue Affective Scale (Watson & Clark, 1994), which measures subjective tiredness and low energy, factors that are known to reduce vigilance and impair signal detection.

ADHD symptoms: Symptoms of ADHD were measured using the World Health Organization (WHO) Adult ADHD Self-Report Scale (ASRS; Kessler et al., 2005). This scale screens for attentional difficulties and impulsivity, making it particularly relevant in studies where divided or reduced attention could affect auditory awareness.

All scales have demonstrated strong internal reliability in prior studies. These individual-level metrics were later used for exploratory

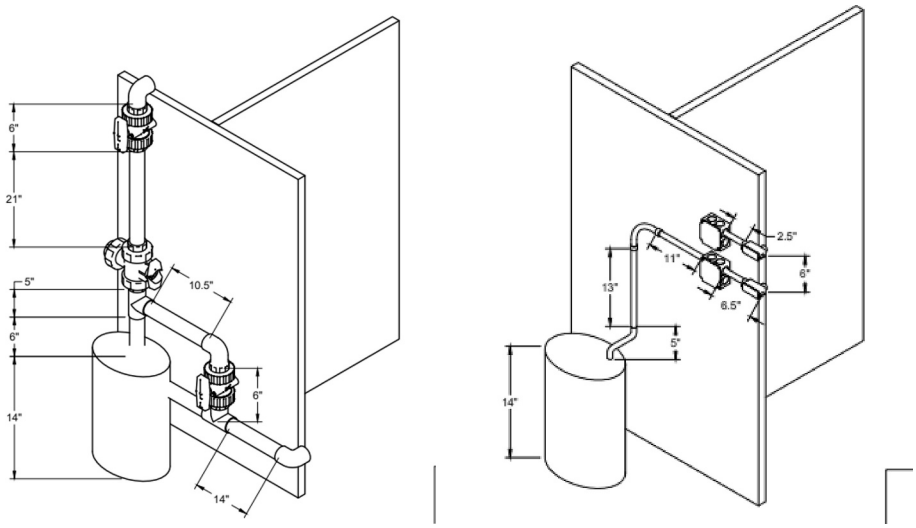


Fig. 2. Mechanical and electrical isometric drawings for side 1.

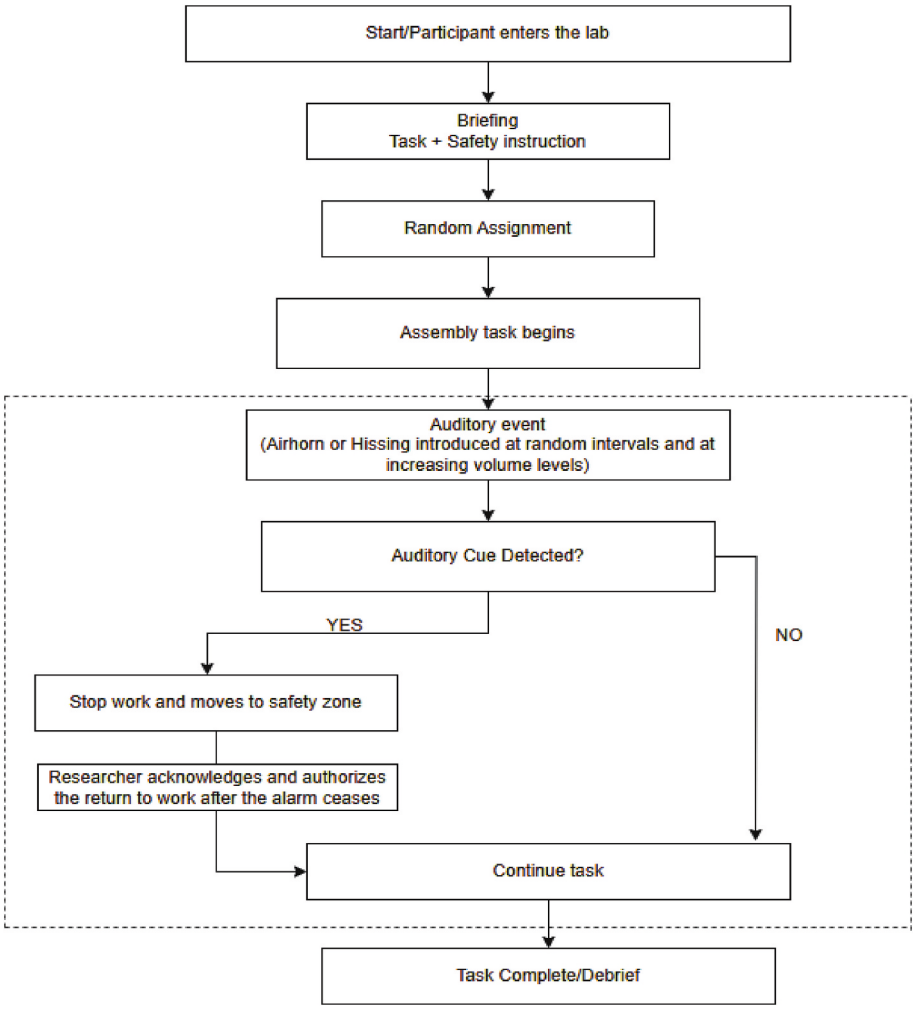


Fig. 3. Flowchart of the Experimental Procedure.

analyses to determine whether personal attributes moderate the possibility of auditory cue detection under varying circumstances.

2.2.2. *Pre-Experiment briefing*

Participants were introduced to the experiment via a structured briefing. They were given a cover story to immerse them in a realistic construction scenario and provided with instructions on how to proceed with the experiment. As per the cover story, participants were to assume they were working in an outdoor construction environment and were '*as workers*' tasked with the responsibility of completing the assembly of mechanical pipe and electrical conduit on an ethylene cracker unit.

As part of this role-play, participants were made aware of the standard site safety protocols. This approach mirrors a typical pre-job safety meeting where workers huddle before work begins to review the planned task, execution strategy, and safety requirements (Bayona et al., 2025; Lingard et al., 2017). To heighten realism, participants were required to wear personal protective equipment (PPE) such as hard hats and safety gloves and were required to inspect their work area before starting to ensure it was hazard-free. They were also instructed to pay attention to their work environment throughout the experiment. They were instructed to stop work and move into the safety zone when they saw a hazard emerge or heard sounds that would indicate they were exposed to a risk. The safety zone was demarcated with tape and mat within the experiment area that the participants would need to enter to indicate they had stopped work. During such stop-work events, the researcher intervened to "resolve" the hazard and authorize the participant to return to work.

To instill productivity pressure, participants were told that their work would be timed, simulating the expectation of efficient performance under job-site conditions. This timing requirement was not merely symbolic but framed as a realistic demand, reflecting how crews are often evaluated on both productivity and safety. In addition, participants were informed that their completion times would be compared against those of their peers, introducing a competitive element. By asking participants to work quickly while maintaining vigilance for safety cues, the experiment reproduced the dual pressures of speed and awareness that characterize construction work.

Once participants confirmed their readiness, they were given printed copies of the 2D ISO drawings and asked to commence putting the MEP system together. Researchers started to time them right after asking them to begin.

2.2.3. *Experiment*

The MEP system had three display panels, and each participant (or pair) was asked to start with Panel 1. This approach is realistic as it mirrors how work would need to be completed and ensures the difficulty level is standardized for all participants. Once participants were engaged in the task, depending on their treatment group (Air Horn vs. Hissing), they would be exposed to an auditory change starting with low volume (81 dB approx.). Each burst of auditory change lasted only 30 s. Once the change was noticed by the participants and they stepped into the safety zone, the researcher would briefly intervene, acknowledge the action,

and authorize them to return to work once the alarm ceased.

2.2.4. Post-Experiment briefing

Following task completion, participants were debriefed and required to complete a post-task questionnaire. This included questions about their overall experience with the task, including their perceived difficulty, and their detection of the auditory changes.

2.3. Participants

A total of 136 participants were recruited for this study. The participants were construction engineering students from the University of Colorado, Boulder, who served as a proxy for inexperienced workers, often referred to in practice as the *green hard hats*. From this pool, 72 participants completed the task individually, while another 64 worked in pairs, yielding 32 pairs. This resulted in a total of 104 experimental runs.

While students may not fully depict the experience of field construction workers, the use of student participants is common both in psychological and construction safety research, particularly in controlled experiments investigating perception, attention, and hazard recognition (e.g., Fu et al., 2024; Hasanzadeh et al., 2018; Sacks et al., 2013). Such studies often use students enrolled in construction-related programs to ethically and practically simulate novice workers' cognitive and perceptual processes before field deployment. The choice of green hard hats also provided an ethically and logistically feasible sample to model attentional and perceptual limitations among early-career construction personnel. Although students were employed in the experiment, they were placed in an ecologically valid environment that recreated the pressures and cues of real jobsites without exposing them to actual harm. By simulating background noise, productivity demands, and safety protocols, the study allowed inexperienced workers to experience conditions that mirrored construction risks in a controlled manner. This approach reflects how industry often trains new workers by placing them in dedicated training centers and workshops, such as utility companies preparing novice linemen on practice poles, where the emphasis is on learning procedures and recognizing risks in a safe but realistic setting. Importantly, inexperienced workers represent a population of particular safety concern, as they are often among the most vulnerable to overlooking subtle but critical changes in their environment precisely because they have not yet developed the pattern recognition or situational awareness of seasoned workers.

While this scoping decision compromises the external validity of the results presented, the use of students allowed us to conduct a controlled experiment and heighten the internal validity. To preserve internal validity, several experimental controls were employed: (1) all participants received identical instructions, (2) the physical task environment and materials remained constant, and (3) the auditory stimuli were calibrated and delivered consistently across trials. Their performance in a controlled environment will provide insights into auditory attention processes in a dynamic environment and be relevant for modeling attentional and perceptual limitations among early-career construction personnel. Demographic data were collected from participants, including age, gender, and self-reported human factors, such as fatigue, negative and positive emotions, and task difficulty. The average age of participants is 22, and the gender distribution is shown in Table 3.

Table 3
Demographics of participants.

Demographics	Sample Size	Percentage
Male	75	55.2%
Female	59	43.3%
Non-Binary/Third Gender	2	1.5%
Total	136	100%

3. Results

The analyses focused on participants' ability to detect auditory cues while performing the construction assembly task under varying conditions. Each stimulus presentation was logged along with the volume level, sound type, and whether participants were working alone or in pairs. All statistical analyses were conducted in R (version 4.4.1; R Core Team, 2024), using RStudio (version 2025.05.1 "Mariposa Orchid ").

Responses to the pre-experiment and post-experiment surveys were also included in the dataset to allow exploration of individual human factors that may influence detection. The dataset comprised binary detection outcomes (1 = detected, 0 = not detected) for each stimulus presentation. The two sound types were contrast coded (Air Horns = +0.5, Hissing = -0.5). The treatment groups were also contrast coded (Pair = +0.5, individual = -0.5). Additionally, for the three-level volume variable, two contrasts were created as shown in Table 4.

These data were analyzed using the lme4 package for generalized linear mixed-effects models (GLMMs) with a logit link. In this analysis, the detection of auditory cues is the dependent variable while other factors, such as volume, sound type, and human factors, are the independent variables. The models included fixed effects for sound type, volume, treatment group (individual vs. pair), and human factors, with random intercepts for participants to account for repeated measures. To facilitate interpretation and support model convergence, all human factor predictors were mean-centered and standardized (z-scored). Multicollinearity among human factors was evaluated using Variance Inflation Factors (VIFs), given their ease of interpretation and ability to capture multivariate relationships. All VIF values were below 1.2 (range = 1.06—1.18), and correlations among standardized predictors were small to moderate ($|r| \leq 0.23$), indicating there was no collinearity among the factors.

In addition to GLMMs, we explored nonlinear patterns using Decision Trees and Random Forests. These models were included in an exploratory capacity to assess potential complex interactions and to generate hypotheses for future research, rather than for confirmatory inference. To the best of the authors' knowledge, previous work on change detection has not applied tree-based ML for predicting inattentional deafness. Variable importance rankings from these models provided complementary insights into the relative contribution of each factor, and model performance was evaluated using 10-fold cross-validation to obtain a reliable estimate of generalization accuracy and minimize overfitting.

3.1. How good are inexperienced workers at detecting auditory changes during work?

The overall detection rate across all participants was 62.2% (Median = 0.667). When broken down by treatment group, the detection rate of participants who worked in pairs is 71%, as they detected sounds more frequently (Median = 1.00). The detection rate of those who worked individually is 58% (Median = 0.667). These results suggest that, on average, inexperienced individuals could miss approximately 40% of auditory changes. Furthermore, individuals working alone were more likely to miss changes compared to those working in pairs. The detection rates for the individual and pair treatment groups are shown in Fig. 4.

Is the performance of pairs meeting expectations based on individual benchmarks?

To assess whether paired participants outperformed statistical expectations, the authors computed predicted detection rates under the

Table 4
Contrast Code for the Volume Level.

	Low	Normal	High
Low vs Normal	0	1	0
Low vs High	0	0	1

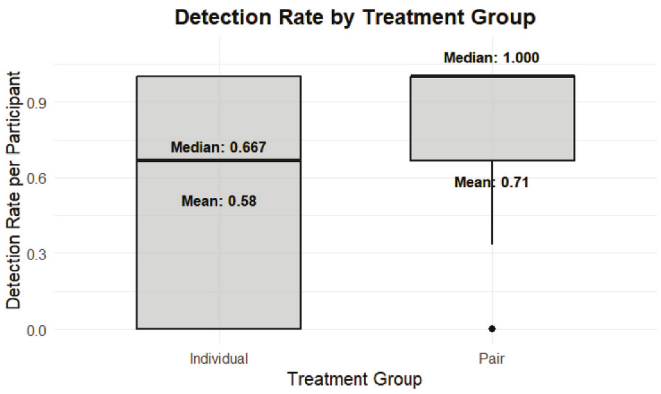


Fig. 4. Boxplot showing detection rate by Treatment group.

assumption of independent detection by individuals. Specifically, for each sound type and volume condition, we calculated the expected probability that at least one member of a pair would detect the change, using formula below:

$$P_{\{pair\}} = 1 - (1 - p)^2 \quad (1)$$

where p is the individual detection probability under each condition.

These expected rates were then compared with the observed detection rates for pairs in the corresponding condition. The observed and expected detection rates are presented in Table 5. This approach provides a meaningful benchmark because it distinguishes between simple probability gains from redundancy (two sets of ears) and actual synergistic benefits of working in pairs. Put differently, it allows us to test whether collaboration creates added vigilance beyond what is statistically expected.

For Hissing sounds, paired performance exceeded statistical expectation at both high (Observed = 75.0%, Expected = 66.0%) and normal volume (Observed = 68.8%, Expected = 59.2%). However, for low-volume condition in Hissing, performance dropped notably below expectation (Observed = 31.2%, Expected = 47.8%), indicating that pairs did not achieve the level of detection predicted from individual performance. In contrast, Air Horn detection was consistently worse *than expected* across all volume levels. The largest deviation occurred under low volume, where the observed detection rate (75.0%) was 20.1% lower than the benchmarked value (95.1%). Even under high and normal volume, observed detection (87.5%) fell below expectations (98.8% and 95.1%, respectively). Because the expected rates account for the probability of at least one member detecting the cue, the fact that observed performance for pairs fell below this benchmark indicates that working in pairs sometimes introduced interference or diffusion effects rather than delivering the redundancy advantage predicted mathematically. However, these deviations were not evaluated with inferential statistical tests; therefore, the comparisons reported here are descriptive and should be interpreted cautiously rather than as evidence of statistical differences. Moreover, because these deviations were not directionally consistent across conditions, working in pairs cannot be considered a reliable safeguard against inattentional deafness.

Table 5
Showing the observed and expected detection rates for sound types at different Volume levels.

Sound Type	Volume	Expected (%)	Observed (%)	Difference (%)	Interpretation
Hissing	High	66.0%	75.0%	+9.0%	Better than expected
Hissing	Normal	59.2%	68.8%	+9.6%	Better than expected
Hissing	Low	47.8%	31.2%	−16.6%	Worse than expected
Air Horn	High	98.8%	87.5%	−11.3%	Worse than expected
Air Horn	Normal	95.1%	87.5%	−7.6%	Worse than expected
Air Horn	Low	95.1%	75.0%	−20.1%	Worse than expected

3.2. What is the impact of the salience of sound on the detection rate?

A generalized linear mixed-effects model was performed to examine the effect of sound type and treatment group on sound detection rates, with a random intercept for participants to account for repeated measures. In formal terms, the first model can be expressed as:

$$\text{logit}\left(p_{ij}\right) = \beta_0 + \beta_S S_{ij} + \beta_G G_{ij} + b_{0j} \quad (2)$$

where S_{ij} represents sound type (Air Horn = +0.5, Hissing = –0.5), G_{ij} represents treatment group (Pair = +0.5, Individual = –0.5), and b_{0j} is a participant-specific random intercept.

The second model examined the interaction between Sound Type (Air Horn vs. Hissing) and Treatment Group (pair vs. individual) on change detection. This was represented as:

$$\text{logit}\left(p_{ij}\right) = \beta_0 + \beta_S S_{ij} + \beta_G G_{ij} + \beta_{SG}\left(S_{ij} G_{ij}\right) + b_{0j} \quad (3)$$

Results revealed a significant main effect of sound type (β_S = 6.81, SE = 2.10, z = 3.25, p value = 0.001). Specifically, detection was significantly higher for Air Horn sounds compared to Hissing sounds. This aligns with expectations, given that Air Horn signals are more distinct, making them perhaps easier to perceive in already noisy environments. The effect of working in pairs or individually was not statistically significant (β_G = –1.62, 95% CI [–3.97, 0.73], which includes zero and, p value = 0.176).

For the second model, there was a significant main effect of sound type, β_S= 7.57, SE = 2.92, z = 2.60, p value = 0.009, with the evidence suggesting the detection rate was higher for Air Horn sounds than Hissing sounds. The main effect of the treatment group was not significant, β_G = -2.66, SE = 2.00, p value = 0.184, suggesting no reliable overall difference in detection between individuals and pairs. Furthermore, the interaction between Sound Type and Treatment Group was also not significant, β_{SG}= 4.96, SE = 4.08, p value = 0.224. This indicates that the advantage of Air Horn over Hissing did not differ meaningfully between individuals and pairs. The corresponding detection rates by sound type and treatment group are shown in Fig. 5.

The results of the two models reveal that detection was significantly higher for Air Horn sounds compared to Hissing sounds. This aligns with saliency expectations. However, whether participants worked alone or in pairs, and how this interacted with the type of sound, did not make a meaningful difference in either model.

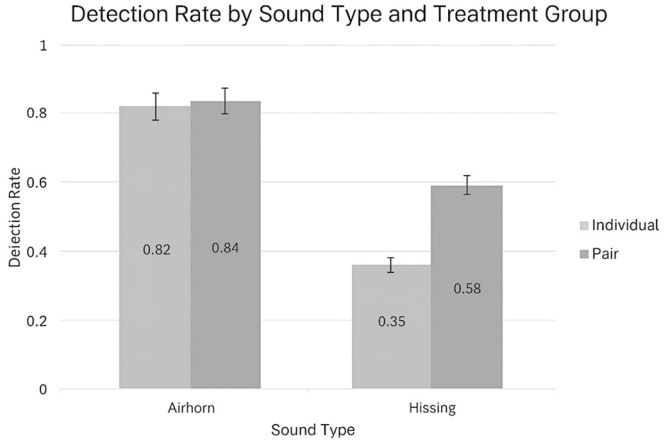


Fig. 5. Bar Chart showing Detection Rate by Sound Type and Treatment Group.

3.3. What is the influence of volume on the detection rate?

To examine whether sound type and loudness influenced detection, we fitted a generalized linear mixed-effects model with a Bernoulli outcome and logit link. The model included fixed effects of Sound Type, Volume (Low, Normal, High), Treatment Group (Individual vs. Pair), and their interactions, as well as a random intercept for each participant to account for repeated measures. The model is expressed as:

$$\text{logit}\left(p_{ij}\right) = \beta_0 + \beta_S S_{ij} + \beta_{VN} V_{N,ij} + \beta_{VH} V_{H,ij} + \beta_G G_{ij} + \beta_{SVN}\left(S_{ij} V_{N,ij}\right) + \beta_{SVH}\left(S_{ij} V_{H,ij}\right) + b_{0j} \quad (4)$$

where $S_{ij} \in$ {-0.5, +0.5} (Hissing = -0.5, Air Horn = +0.5), $V_{N,ij} = 1$ for Normal volume and 0 otherwise, $V_{H,ij} = 1$ for High volume and 0 otherwise (as Low is the reference), $G_{ij} \in$ {-0.5, +0.5} for Group (individual = -0.5, pair = +0.5), and $b_{0j} \sim \mathcal{N}\left(0, \sigma_b^2\right)$ is a participant random intercept.

Results revealed a significant main effect of Sound Type: participants were more likely to detect Air Horn sounds compared to Hissing sounds, $\beta = 22.33$, SE = 4.05, z = 5.52, $p < 0.001$. There was also a significant main effect of volume: detection improved at both Normal ($\beta = 3.42$, $p = 0.005$) and High ($\beta = 6.56$, $p = 0.005$) levels compared to Low volume. Although the interaction between Sound Type and Volume (Normal) was only marginal ($\beta_{SVN} = -3.81$, p value = 0.082), it suggests that the benefit of increasing volume from Low to Normal may be less pronounced for Air Horns than for Hissing. The interaction with High volume was non-significant.

The treatment group did not have a significant main effect (p value = 0.48), suggesting that detection differences were primarily driven by stimulus characteristics rather than social condition in this model. The corresponding detection rates by volume and sound type are shown in Fig. 6.

Overall, this analysis suggests that less distinct sounds, such as Hissing, are harder to detect, especially at lower volumes, meaning that low-energy auditory changes are more likely to be missed on worksites regardless of social context.

To examine whether successive detections were correlated within individuals, an additional lagged analysis was conducted. A previous detection variable was created to indicate whether the participant detected the immediately preceding cue within the ordered volume sequence. Detection at Trial 2 and Trial 3 was then modeled as a function of previous detection, sound type, volume, and treatment group. Descriptively, when the preceding cue was not detected, the subsequent detection rate was 25.3%; however, when the preceding cue was detected, the subsequent detection rate increased to 96.7%. The logistic regression model showed that previous detection was a significant predictor of subsequent detection, $\beta = 4.28$, SE = 0.59, z = 7.25, $p < 0.001$. This corresponded to an odds ratio of 72.5, indicating that participants were substantially more likely to detect a cue if they had detected the immediately preceding cue. Adding previous detection also significantly improved model fit compared with the model without the lagged predictor, $\chi^2(1) = 12.17$, $p < 0.001$. A follow-up interaction model showed that the effect of previous detection did not significantly vary by volume level, suggesting that the lagged effect was not simply explained by the increase from normal to high volume.

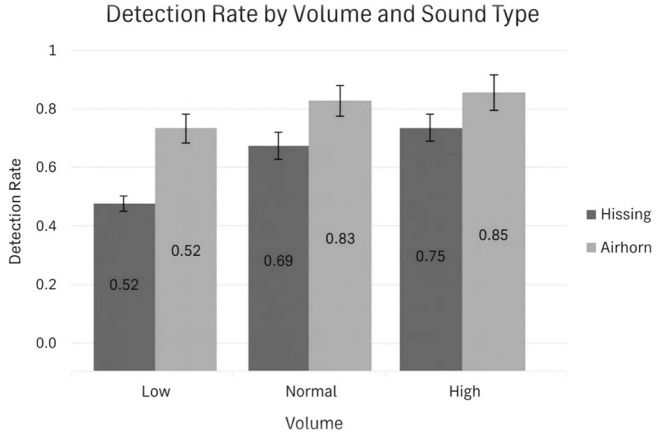


Fig. 6. Bar Chart showing Detection Rate by volume and Sound Type.

3.4. What is the influence of human factors on the detection rate?

A generalized linear mixed model (GLMM) was fitted to examine whether individual-level psychological factors (fatigue, ADHD symptoms, task difficulty, and emotional states) predicted the likelihood of detecting auditory signals, controlling for treatment group (individual vs pair). Before running the model, descriptive statistics for the predictors and detection rate were calculated (Table 6).

A participant-level random intercept was included to account for the non-independence of repeated measures within individuals. This step is important because responses from the same participant are likely correlated, and failing to account for this dependency would inflate Type I error rates and bias the estimation of fixed effects. The analysis model with a Bernoulli outcome and a logit link is expressed as below:

$$\text{logit}\left(p_{ij}\right) = \beta_0 + \beta_F F_{ij} + \beta_A A_{ij} + \beta_T T_{ij} + \beta_p P_{ij} + \beta_N N_{ij} + \beta_G G_{ij} + \beta_{FT}\left(F_{ij} T_{ij}\right) + b_{0j} \quad (5)$$

Where F_{ij}, A_{ij} and T_{ij} are the z-scored Fatigue, ADHD, and Task Difficulty scores, respectively, for trial I of participant j; P_{ij} and N_{ij} represent positive and negative emotions, respectively $G_{ij} \in$ {-0.5, +0.5} codes treatment Group (Individual = -0.5, Pair = +0.5); and $b_{0j} \sim b_{0j} \sim \mathcal{N}\left(0, \sigma_b^2\right)$ is a participant-specific random intercept.

To examine whether the effect of fatigue on detection depends on task difficulty, an interaction term (Fatigue × Task Difficulty) was included in the model. Prior to fitting the model, potential collinearity among the human-factor predictors was examined. Variance Inflation Factors (VIFs) were all close to 1 (range = 1.03–1.18), indicating no evidence of multicollinearity. To further evaluate interrelationships, a correlation matrix of the standardized predictors was computed (Table 7). Correlations were small to moderate ($|r| \leq 0.23$), consistent with theoretically related but distinct constructs, confirming that multicollinearity was not a concern.

The model did not reveal any statistically significant effects of the centered and scaled human factor predictors on detection:

1. Fatigue, although positively related to detection ($\beta_F = 0.60$, $p = 0.294$), the effect was not statistically significant. ADHD symptoms were negatively related to detection but the effect was not statistically significant ($\beta_a = -0.18$, $p = 0.737$).
2. Task Difficulty ($\beta_t = -0.40$, $p = 0.475$), Negative Emotions ($\beta_n = -0.11$, $p = 0.838$), and Positive Emotions ($\beta_p = 0.15$, $p = 0.781$) all had non-significant effects.
3. The effect of the Treatment Group (β_G was also not statistically significant ($\beta_G = -1.68$, p value = 0.166).

Table 6
Descriptive statistics for detection and human-factor predictors.

Variable	Mean	SD	Min	Max
Detection	0.62	0.49	0.00	1.00
Fatigue	2.10	0.80	0.88	4.00
ADHD	2.68	0.56	1.58	4.83
Task Difficulty	2.62	0.98	0.00	5.00
Positive Emotion	2.85	0.72	1.00	5.00
Negative Emotion	1.29	0.36	0.50	2.80

Table 7
Correlations among centered and scaled human-factor predictors.

Predictor	Fatigue	ADHD	Task Difficulty	Negative Emotions	Positive Emotions
Fatigue	1.00	0.08	0.05	0.22	−0.17
ADHD	0.08	1.00	0.10	0.16	−0.02
Task Difficulty	0.05	0.10	1.00	0.23	0.00
Negative Emotions	0.22	0.16	0.23	1.00	0.16
Positive Emotions	−0.17	−0.02	0.00	0.16	1.00

Note. Correlations computed from standardized predictors. All $|r| \leq 0.23$, confirming absence of problematic multicollinearity.

The intercept was significant ($p = 0.007$), indicating above-chance detection at average levels of the predictors. None of the human factors significantly influenced the detection rate in this model, and the interaction between Fatigue and Task Difficulty was also nonsignificant, indicating that the effect of fatigue on detection did not vary systematically across levels of task difficulty. These findings should be interpreted cautiously. Although the dataset included 312 observations, the effective sample size is reduced due to the inclusion of participant-level random effects in the logistic mixed model, which accounts for within-subject dependence and limits sensitivity to detect smaller effects. An approximate post hoc evaluation indicates that the study had limited power to detect small to moderate effects, therefore, the null results should be interpreted as inconclusive rather than evidence of no relationship. It is possible that subtle influences of fatigue, ADHD symptoms, task difficulty, or emotional states on detection exist but were not detectable in the present study. Additionally, the use of self-reported, single-time-point measures may have limited the ability to capture meaningful within-person variation across trials. It is possible that a larger sample size, physiological measures, or field-based settings may be required to detect subtler effects. At minimum, these null findings highlight that the examined individual-level psychological states did not significantly account for variability in inattentional deafness in this study, paralleling prior work showing that detection skills, such as hazard recognition, are also not strongly predicted by internal states (Bhandari et al., 2020).

3.5. Exploratory Machine learning results

To complement the confirmatory regression models and probe whether the experimental factors combined in nonlinear ways that may not be fully captured by parametric approaches, the authors employed machine learning models in an exploratory capacity. Specifically, a classification tree and a random forest model were fitted to examine how sound type, volume, and treatment group interact to shape detection outcomes. A classification tree is a simple predictive model that splits the data into branches based on rules (for instance, "if sound type = airhorn, then higher detection"), creating a tree-like structure that highlights conditional relationships. A random forest extends this idea by building many such trees on different subsets of the data and then averaging their predictions, which improves accuracy and reduces overfitting. Together with heat map visualizations, they offer additional perspective on which experimental factors most strongly influenced auditory detection. These machine learning models are described in Hastie et al. (2001), and they have been applied to modeling construction injury (Tixier et al., 2016; Tixier & Hallowell, 2023). The resulting classification tree is presented in Fig. 7.

The classification tree highlights Sound Type as the first-level split, suggesting it is the strongest determinant of detection. The tree shows that Air Horn sounds overwhelmingly led to detections (node labeled "1″ with 82% detection rate), irrespective of treatment group. In contrast, detection outcomes for Hissing sounds depended on whether

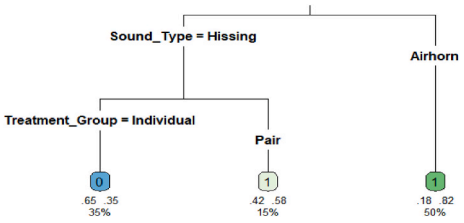


Fig. 7. Classification (Decision) Tree Model for Detection Probability.

participants worked individually or in pairs. This second-level split reveals an interaction, where collaboration improved detection specifically under low-salience Hissing conditions (Pairs = 58% vs. Individuals = 35%).

The random forest model further corroborated these findings with variable importance plots in Fig. 8 indicating Sound Type as the most critical predictor of detection accuracy.

Sound Type had the highest mean decrease in both Accuracy and Gini impurity (a measure of how well a variable splits the data into distinct classes; higher values indicate that the predictor reduces classification uncertainty more effectively), underscoring its dominant role in shaping detection outcomes. Volume ranked second, particularly in the Mean Decrease Gini metric, reinforcing its moderate yet meaningful contribution. The Treatment Group showed the least importance among the three predictors, echoing earlier statistical findings that group dynamics, while occasionally helpful, were less consistently influential than sound characteristics.

To evaluate the generalizability of these models, a 10-fold cross-validation was performed for both the classification tree and the random forest. Cross-validation estimates each model's predictive accuracy on unseen data. It does this by repeatedly training the models on a subset of the data and testing it on the held-out portion. From the cross-validation analysis, the classification tree achieved a mean cross-validated accuracy of 0.71. This indicates a moderate predictive reliability and supports its interpretive value. On the other hand, the random forest achieved a higher cross-validated accuracy of 0.74. This is consistent with the expectation that ensemble approaches provide more stable generalization and reduced overfitting. These validation results reinforce the substantive interpretation that detection performance is primarily driven by stimulus salience, with volume exerting a secondary role, and collaborative advantage emerging only under low-salience auditory contexts.

Together, the decision tree and random forest results provide converging evidence that detection is primarily driven by stimulus properties, namely, the salience (sound type) and volume, while social

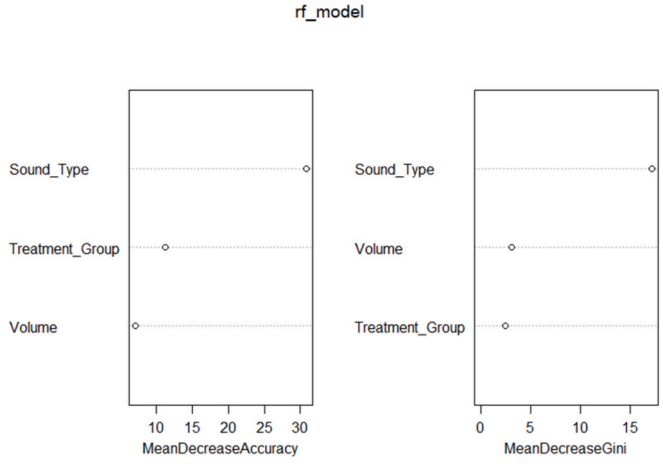


Fig. 8. Variable Importance graph from Random Forest Model of Detection Probability.

context (individual vs. pair) plays a secondary role. These findings align well with the GLMM results and offer robust model-based confirmation of the observed experimental patterns.

Furthermore, the heatmap in Fig. 9 offers a consolidated visual summary of detection rates across combinations of Volume, Treatment Group, and Sound Type. A clear pattern emerges as detection rates were uniformly higher for Air Horn sounds (darker shades), regardless of volume or social condition. In fact, all Air Horn conditions show detection rates above of approximately 0.75 or higher, confirming their high salience and consistent detectability.

In contrast, Hissing sounds displayed much more variability. Detection was lowest in the Individual + Low Volume condition (lightest shade), aligning with earlier findings that subtle cues are difficult for individuals to detect. Notably, Pair + High Volume for Hissing achieved comparable detection levels to some Air Horn conditions, suggesting that both collaborative context and increased volume help compensate for low salience signals. This heatmap thus reinforces the dominant influence of Sound Type, while also visually illustrating the nuanced effects of Volume and Treatment Group under less salient conditions.

4. Discussion

This study documents evidence of inattentional deafness within the construction context and presents implications for safety practices. Despite participants being aware of being in an experimental setting, they missed a substantial number of safety–critical auditory cues. On average, participants were only able to notice 58% of sounds when working individually. Based on individual performance, pairs should have detected approximately 84% of cues, yet their actual detection rate (71%) was considerably lower. Thus, the comparison between individuals and pairs demonstrates that collaboration improves detection but falls short of its probabilistic potential. This underperformance suggests that working in pairs introduces new dynamics such as diffusion of responsibility, attentional synchronization, or coordination failures, which may reduce the redundancy benefit of having two people. It is also possible that detection performance may plateau beyond a certain threshold, regardless of collaboration. Theoretically, this challenges assumptions that pair-based collaboration is always compensatory, and practically, it cautions against viewing a two-person team as a reliable safeguard against inattentional deafness. It will deliver marked improvement over solo work, but not guaranteed detection. It is also important to note that this study examined pairs only; the dynamics of larger crews may differ in ways not captured here.

The benefits of collaboration were also not uniform across all conditions. The decision tree results provide empirical support for this pattern: pairs outperformed individuals for low-salience Hissing cues (58% vs. 35% detection), suggesting that a second set of ears is particularly beneficial when individual detection is most vulnerable.

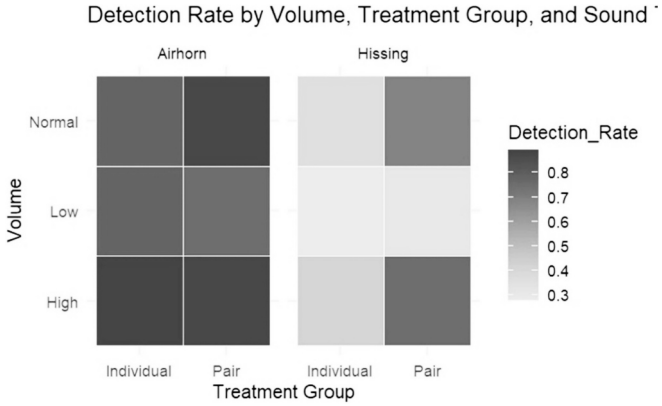


Fig. 9. Heatmap for Detection Rate by Volume, Treatment Group, and Sound.

However, for Air Horn cues at low volume, pairs observed a detection rate of 75.0% against an expected rate of 95.1%, a gap of over 20 percentage points. This goes against the grain of prior assumptions that teamwork consistently enhances safety, with the underperformance of pairs in detecting low-volume Air Horns directly challenging expectations of mutual monitoring (Cymek, 2018; Williams & Karau, 1991). This inconsistency suggests that group dynamics may sometimes introduce interference effects that offset the expected advantage.

Unsurprisingly, the detection rate was significantly influenced by the characteristics of the change simulated, consistent with findings from other domains. Within context, Hissing would represent accidental energization of the system participants are working on, posing an immediate threat. However, even when controlling for volume and treatment group, distinctive sounds such as the Air Horn were detected far more reliably than the subtler Hissing sounds. It would indicate that salience can counter cognitive bottlenecks (Cvach, 2012; Dehais et al., 2014) to improve detection rates. Volume exerted a meaningful effect on low-salience cues, with louder Hissing being detected more often. These findings reaffirm longstanding theories that perceptual salience can break through attentional bottlenecks, while subtle cues are more vulnerable to being overlooked. For safety practice, this suggests that alarm design should emphasize distinctiveness rather than simply increasing loudness. Signals that resemble background noise are at higher risk of being ignored unless deliberately amplified or differentiated.

The successive detection analysis further suggests that detection was not independent across repeated cue presentations. Participants who detected the immediately preceding cue were far more likely to detect the next cue, even after accounting for sound type, volume, and treatment group. This pattern suggests that once participants became aware of an auditory change, they may have entered a heightened state of expectation or vigilance, making subsequent cues easier to notice. This finding is important because it indicates that detection may be dynamically shaped by prior awareness, not only by the physical properties of the sound. In practical terms, this means that the first missed cue may be especially consequential: if workers fail to notice an initial subtle auditory change, they may be less likely to become attuned to subsequent changes in the environment.

Contrary to expectations, individual-level human factors such as fatigue, emotional state, and ADHD symptoms did not significantly predict detection. While this may reflect genuine limits in short, structured tasks, it could also stem from the use of self-reports rather than physiological measures or from the relatively homogenous student sample. Prior work suggests these factors may matter more over longer durations or in more complex environments (Muñoz-La Rivera et al., 2021; Yue et al., 2024). In practice, this implies that inattentional deafness cannot be reliably mitigated by assuming that rested or emotionally balanced workers will notice more cues. Instead, system-level interventions in alarm design and work structuring are needed regardless of workers' momentary psychological states.

Rather than treating inattentional deafness as an individual failure, these findings emphasize that it is a systems-level characteristic and highlight the need for safety practice to be grounded in realistic expectations of human perception. It is a natural cognitive phenomenon, and expecting workers to reliably detect every relevant change is not only unreasonable but impossible. The more appropriate direction for practice is to reduce reliance on constant vigilance by designing cues that are more salient, by avoiding situations where workers must operate alone without redundancy, and by anticipating when and where changes are most likely to occur so that controls can be structured in advance rather than depending on in-the-moment detection. These findings connect meaningfully to established theoretical frameworks in attention research. Consistent with Kahneman's (1973) Capacity Model, the results confirm that when primary task demands are high, insufficient attentional resources remain available to register concurrent auditory signals. The dominance of sound type as a predictor aligns with

Treisman's (1964) Attenuation Theory, which predicts that highly salient signals are more likely to exceed the threshold for conscious awareness even when attention is directed elsewhere. The underperformance of pairs relative to probabilistic expectations is consistent with Cymek's (2018) findings on redundant monitoring, suggesting that the supervisory attentional system (Norman & Shallice, 1986) may disengage when workers assume a partner is monitoring. Together, the empirical pattern supports a view of auditory detection as a shared cognitive and systemic challenge, not simply an individual perceptual one.

From a practical standpoint, these findings have implications for alarm design standards and safety management on construction sites. Current industry guidance generally requires that auditory warning signals be audible above background noise, but does not systematically account for the attentional mechanisms documented here. The evidence suggests that distinctiveness, how much a sound differs perceptually from the ambient soundscape, is perhaps more important than the raw decibel level. Signals that resemble environmental noise, such as the Hissing cue used in this study, remain vulnerable to being missed even at volumes that technically exceed background levels. This has implications for how safety alarm systems are designed and verified: purely acoustic testing of signal-to-noise ratios may be insufficient without also accounting for perceptual salience under realistic cognitive load conditions. Organizationally, the finding that solo workers miss roughly 40% of auditory cues challenges policies that permit single-person operation in high-risk areas without compensating controls. Minimum crew sizes, buddy systems, or automated alert systems may be warranted where auditory detection is safety–critical. Safety training programs could also be strengthened by explicitly teaching workers about the limits of their own attentional capacity and the conditions under which those limits are most likely to be exceeded, rather than simply instructing them to "stay alert."

5. Limitations

Although this study provides insight into susceptibility to inattentional deafness during construction tasks, the findings should be considered in the context of the study's methodological limitations. Firstly, the sample consisted of construction engineering students rather than field workers. These students served as a proxy for inexperienced and green hat workers, but their situational awareness would be expected to differ from that of moderately or extensively experienced workers. Therefore, the external validity of the results presented is limited. Second, the study was hosted in a controlled environment. Although the experiment incorporated realistic construction activities and noise levels, it could not fully reproduce the dynamic conditions of an active job site where competing hazards, communication demands, weather exposure, and simultaneous tasks likely amplify inattentional deafness. However, the controlled setting did enhance internal validity of the study. The use of a simulated environment was intentional, since replicating a real construction environment would require introducing cognitive load while workers perform actual work, which carries an unacceptable risk of masking or creating changes that could endanger workers' lives. Moreover, prioritizing internal validity allowed the study to isolate attentional mechanisms without the confounding influence of uncontrolled field conditions. Nevertheless, future research should examine whether these findings generalize across workers with differing backgrounds, roles, and levels of experience. Third, the auditory stimuli used were limited to two types of sounds: Air Horn and the Hissing sound, and were presented at three fixed intensity levels. Real construction environments include a broad range of auditory cues that vary in salience, frequency, and meaning. Including additional warning types or interventions would have required a substantially larger sample to maintain statistical power, which was logistically infeasible for a controlled laboratory experiment of this scope. Fourth, the experimental task involved only one activity that required reading drawings and completing a mechanical–electrical assembly. Although cognitively demanding, this single-task framework does not represent the diversity of physical and perceptual demands across construction tasks, which may influence susceptibility to inattentional deafness. Fifth, the human factors variables were measured using self-reported, single-time-point scales, which may have limited the ability to capture meaningful within-person variation across trials. Future research should include a formal psychometric or physiological validation of cognitive load, including heart rate variability, cortisol, and EEG-derived workload indices. Sixth, given the study design, causality cannot be established. Associations between factors such as sound type, volume, and detection can be observed, but causal mechanisms cannot be fully confirmed. Seventh, participants worked either individually or in pairs, whereas real crews often operate in larger, unevenly sized groups with more complex communication dynamics and distributed attention patterns. The finding that pairs did not fully meet probabilistic detection expectations applies specifically to two-person collaborations. Eighth, the fixed order of increasing volumes (81, 83, 85 dB) limits interpretation because volume was not randomized and may be confounded with order and learning effects. It is not possible from this design to fully disentangle whether improvements in detection at higher volumes reflect acoustic salience, habituation to the task, or growing expectation of the cue. Future research should present volumes in randomized order to enable this separation. Ninth, each auditory cue was presented for 30 s, which may have been too brief for fatigue or emotional state to manifest, although fatigue and emotional state were conceptualized as baseline individual differences rather than states induced by the auditory stimuli. Accordingly, the exposure duration was not intended to generate within-trial variation in these factors, but rather to assess how pre-existing conditions relate to detection performance. The study was also conducted in a single sitting, either in the morning or early afternoon, and it remains unknown whether results would differ at the end of a work shift, when fatigue accumulates over longer durations. Tenth, participants were not pre-exposed to the auditory cues prior to the experiment as part of standardized training, which mirrors the green hard hat experience of workers who arrive on site without prior familiarity with site-specific alarm sounds. While this enhances ecological validity for the target population, it means that the findings may not generalize to experienced workers who have developed familiarity with particular auditory signals. Eleventh, the behavioral measure used, moving to a designated safety zone, serves as a proxy for auditory detection and more specifically measures response compliance. A small number of participants may have heard a cue but been uncertain whether to stop work, which could slightly undercount true detection. Future studies may benefit from combining behavioral response measures with verbal reports or physiological indicators to better isolate detection from compliance. Taken together, these limitations indicate that although the study provides clear evidence of inattentional deafness in a safety–critical context, further research using more ecologically valid settings, expanded stimulus sets, larger and more diverse samples including variation in age and experience, crew-based work structures, and designs that allow causal inference is needed to fully understand the phenomenon and its implications for construction safety.

6. Conclusions

This study provides empirical evidence of inattentional deafness in a construction context. Results show that sound type and volume emerged as the strongest determinants of detection, with distinctive sounds like Air Horn (i.e., alarms) detected more reliably than subtler cues such as Hissing (i.e., hazardous energy). Collaboration in pairs improved detection compared to working alone, but performance fell short of probabilistic expectations, revealing that working in pairs is not a guaranteed safeguard against inattentional deafness. It is important to note that this finding applies specifically to pairs; the effects of larger crew sizes remain an open question. Academically, this study represents

the first investigation to capture the extent to which inexperienced employees could be susceptible to inattentional deafness. It revealed that individual cognitive traits such as fatigue, emotions, and task difficulty had no measurable effect on detection, underscoring the limits of cognition as a buffer against missed cues. Instead, the characteristics of change itself proved most important, with salience and volume being the strongest determinants of auditory awareness. Practically, these findings indicate that safety cannot rely on the assumption that workers will consistently notice auditory changes in the moment. Alarm systems should prioritize distinctiveness and avoid resembling background noise, while organizational strategies should minimize solo work and anticipate high-risk changes rather than depending on constant vigilance. Altogether, the findings serve as an early benchmark for understanding how auditory lapses can emerge even in a controlled laboratory simulation. Because the experiment was conducted in a controlled setting with a homogeneous student sample and a circumscribed task, caution is warranted before generalizing these results to all construction workers, work types, or field environments. Real-world job sites, with more varied cognitive demands, higher stakes, longer shift durations, and greater workforce diversity, may present both greater challenges and different patterns of inattentional deafness than those observed here. Additionally, the sample consisted predominantly of young adults with a mean age of 22 years, and participants were not formally screened for pre-existing hearing impairment prior to enrollment. Future research should verify normal hearing thresholds as part of participant screening and ensure representation of older workers, for whom age-related hearing decline may compound susceptibility to inattentional deafness. These findings nonetheless highlight the need for safety systems that account for human attentional limitations rather than assuming reliable detection. Future work should examine the roles of worker experience, age, crew-size dynamics, and shift-related fatigue in shaping susceptibility to inattentional deafness and should extend testing into more ecologically valid field conditions and longer work durations to determine whether these laboratory-based patterns hold at scale.

CRediT authorship contribution statement

Abayomi A. Oladejo: Writing – review & editing, Validation, Writing – original draft, Methodology, Conceptualization, Formal analysis, Visualization, Data curation. **Siddharth Bhandari:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Lynneatte P. Quenin:** Writing – review & editing, Validation, Methodology. **Leaf Van Boven:** Writing – review & editing, Validation, Methodology. **Matthew Morris:** Writing – review & editing, Validation, Methodology, Conceptualization. **Balaji Rajagopalan:** Writing – review & editing, Validation, Methodology. **Matthew Hallowell:** Writing – review & editing, Validation, Methodology, Funding acquisition.

Declaration of competing interest

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

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