Road Construction Workers' Boredom Susceptibility, Habituation to Warning Alarms, and Accident Proneness: Virtual Reality Experiment

Namgyun Kim, A.M.ASCE[1]; Niya Yan[2]; Laurent Grégoire[3]; Brian A. Anderson[4]; and Changbum R. Ahn, A.M.ASCE[5]

Abstract: Every year more than 100 fatal accidents occur in road work zones. One of the major causes of pedestrian workers being struck by construction vehicles is that workers become habituated to the warning alarms of these vehicles. Researchers suggest that workers with certain personality traits (e.g., boredom proneness and extraversion) are more likely to become habituated to workplace hazards and therefore have a higher likelihood than other workers of being involved in an accident. This study investigated which aspects of personality correlate with workers' accident proneness and their vulnerability to habituation to warning alarms in road work zones. An experiment with actual road construction workers was performed using a virtual reality (VR) environment. The results reveal that boredom susceptibility (one of the subdimensions of the personality trait of sensation seeking) is negatively correlated with workers' attention to warning alarms, and that boredom-prone workers were more likely to be involved in a virtual struck-by accident. The findings of this study provide conceptual motivation for tailoring safety training to individual workers' personality traits. **DOI: 10.1061/JCEMD4.COENG-12818.** © *2022 American Society of Civil Engineers.*

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Introduction

Fatalities in road work zones account for about 9% of all fatalities in the construction industry (CPWR 2018). Specifically, runovers and backovers by heavy construction vehicles are the leading causes of fatalities in road work zones (BLS 2019; CPWR 2018). In many instances, construction vehicles were moving at a low speed, and auditory warning alarms were functioning, but pedestrian workers involved in accidents failed to notice the vehicles (Pegula 2013). Previous studies showed that workers are apt to become habituated to warning alarms from construction vehicles that constantly beep in road work zones (Duchon and Laage 1986; Glendon and Litherland 2001; Pratt et al. 2001). Pedestrian workers' attention to warning alarms decreases with prolonged exposure to those alarms, and such decreased attention can result in fatal struck-by accidents between construction vehicles and pedestrian workers (Luo et al. 2016; Marks and Teizer 2013; Pratt et al. 2001; Duchon and Laage 1986; Daalmans and Daalmans 2012; Kim et al. 2021a). Construction workers are asked to take periodic safety training and are informed of the risks of being run over or backed over by construction vehicles in an effort to maintain their attention to workplace hazards; however, after working around construction vehicles for some time, workers still tend to become inattentive to vehicle warning alarms (Chan et al. 2020; Kim et al. 2021b; Pratt et al. 2001). Furthermore, research found that some individual workers are more likely than others to be habituated easily and to be inattentive to frequently encountered hazards in road work zones (Kim et al. 2021a). Thus, investigating the human factors that affect workers' habituation to repeated alarms is essential within the field of construction safety management.

Psychology research has established that individual differences in personality traits play a critical role in the human ability to sustain attention to repeated or prolonged external stimuli, especially for workplace hazards (Cummings et al. 2016; Finomore et al. 2009; Watt and Morris 1995). For example, an individual's sensation-seeking propensity is highly associated with engaging in risky behaviors and experiencing injuries and accidents (Eastwood et al. 2012; Zuckerman 1979; Zuckerman and Neeb 1979). Furthermore, analysis of accident reports showed that specific construction workers were involved in injuries and accidents at work more frequently than other workers (Clarke 2016; Mayer et al. 1987; Sing et al. 2014). Such individuals who repeatedly are involved in workplace accidents have been defined as accident-prone (Farmer and Chambers 1926; Reason 1974). Recent studies in construction safety have suggested that construction workers with high scores in the area of sensation seeking tend to be less attentive to frequently

[1]Assistant Professor, Dept. of Civil and Environmental Engineering and Engineering Mechanics, School of Engineering, Univ. of Dayton, Dayton, OH 45469. ORCID: https://orcid.org/0000-0002-0342-9772. Email: nkim01@udayton.edu

[2]Ph.D. Student, Dept. of Psychological and Brain Sciences, College of Liberal Arts, Texas A&M Univ., College Station, TX 77843-4235. Email: yanniya@tamu.edu

[3]Postdoctoral Researcher, Dept. of Psychological and Brain Sciences, College of Liberal Arts, Texas A&M Univ., College Station, TX 77843-4235. ORCID: https://orcid.org/0000-0002-3519-6395. Email: lgregoire1@tamu.edu

[4]Associate Professor, Dept. of Psychological and Brain Sciences, College of Liberal Arts, Texas A&M Univ., College Station, TX 77843-4235. Email: brian.anderson@tamu.edu

[5]Associate Professor, Dept. of Architecture/Architectural Engineering, Seoul National Univ., Seoul 08826, South Korea (corresponding author). ORCID: https://orcid.org/0000-0002-6733-2216. Email: cbahn@snu.ac.kr

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encountered hazards and tend to engage in unsafe behaviors at construction sites more frequently (Hasanzadeh et al. 2020a; Sun et al. 2020). Specifically, boredom susceptibility—one of the subdimensions of an individual's sensation-seeking propensity—has been shown to be an underlying cause of inattentive behaviors at work (Shaw et al. 2010; Tam et al. 2021; Yakobi and Danckert 2021), but many questions remain regarding which personality traits best explain workers' vulnerability to habituation to warning alarms, and how personality is associated with an individual's accident proneness. To date, no controlled studies have directly investigated the influence of personality traits on the tendency of workers to be involved in a struck-by accident in road work zones, because of the absence of a method to measure workers' habituated inattention in a construction context.

To address these knowledge gaps, this study (1) investigated whether road construction workers' sensation-seeking tendency is associated with habituation to repeated auditory warning alarms from construction vehicles in road work zones, and (2) examined how individual differences in personality traits affect the tendency to be involved in a struck-by accident. Our experiment was performed with actual road construction workers using a virtual reality (VR) environment. Our findings reveal which aspects of sensation seeking correlate with workers' vulnerability to habituation to warning alarms in road work zones. Our outcomes also provide empirical evidence for a relationship between personality traits and the likelihood of workers' accident involvement in workplaces, which has been noted anecdotally but underexplored academically. Consequently, this study provides an important opportunity to further understand workers' habituation to warning signals and struck-by hazards, thereby contributing to the design of safety training and intervention strategies that effectively prevent struck-by accidents in road work zones.

Research Background

A number of studies have suggested an association between personality traits and unsafe behaviors. This section reviews the theoretical foundation of the impact of individual personality traits on habituation to workplace hazards and discusses the knowledge gaps that exist for empirically assessing the relationship between personality traits and workers' accident proneness.

Workers' Habituation to Warning Alarms in Road Work Zones

Habituation has been defined as a decrease in the amplitude of responses to repeated sensory stimulation, which is a type of sensory adaptation to a repeated external stimulus (Bukatko and Daehler 2012; Picton et al. 1976; Thompson and Spencer 1966). Fig. 1 shows the hypothetical habituation curve in responses to a repeated stimulus (Avery and Blackford 2016; Ishai et al. 2004; Schmid et al. 2015). Habituation also can be defined as cumulative adaptation. The increase in the number of exposures to a stimulus leads to a weakening of responses (Petrinovich and Patterson 1982; Thompson and Spencer 1966). Specifically, human sensory responses to auditory stimuli diminish, and such habituation results in loss of attention to the auditory stimuli (Ritter et al. 1968).

Recent studies have linked construction workers' habituated inattention to warning alarms and workers' involvement in struck-by accidents in road work zones (Chan et al. 2020; Kim et al. 2021b; Sakhakarmi et al. 2019). Pedestrian workers in road work zones are at a high risk of being struck by construction vehicles (e.g., dump trucks, milling machines, rollers, and street sweepers) because road

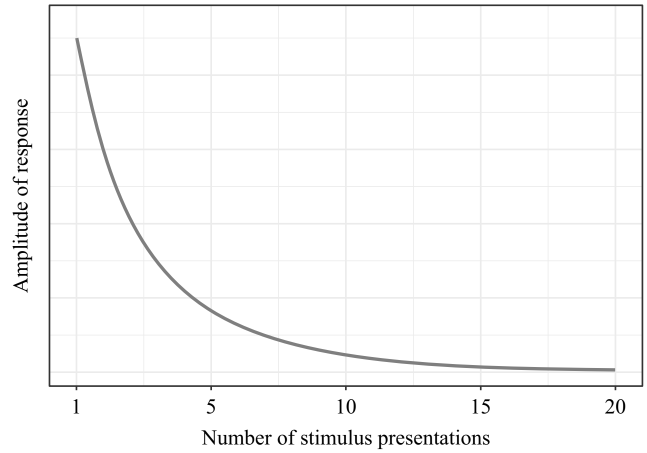


Fig. 1. Hypothetical habituation curve in responses to a repeated stimulus according to Avery and Blackford (2016).

maintenance and construction tasks include frequent worker–vehicle interactions (Fan et al. 2014). Every year, more than 100 fatal accidents occur in road work zones in the US (CPWR 2018). In particular, struck-by accidents between a pedestrian worker and a construction vehicle account for more than 50% of those fatalities in road work zones (BLS 2019; Fan et al. 2014; CPWR 2018). In road work zones, construction vehicles use auditory alarms to warn pedestrian workers about their proximity. However, pedestrian workers are likely to become habituated to alarms when the alarms are repeated, unnecessary, and redundant, and this may lead workers to ignore true alarms that are indicative of hazards (Luo et al. 2016; Marks and Teizer 2013; Sendelbach and Funk 2013). Consequently, workers' habituation to vehicle alarms is one of the principal factors in runover and backover accidents in road work zones. In many instances of fatalities in road work zones, dump trucks were backing up and sounding warning alarms; however, workers tuned out the alarms (Daalmans and Daalmans 2012; Pegula 2013). Therefore, preventing workers' habituation to alarms from vehicles is essential to improving safety in road work zones.

Personality Traits, Unsafe Behaviors, and Accident Proneness

Psychology and learning science research reveals the role of individual personality traits in relation to unsafe or risky behaviors in dangerous situations (Beus et al. 2015; Eastwood et al. 2012; Janicak 1996). Construction safety research has attempted to identify factors of personality traits that influence workers' engagement in unsafe or risky behaviors (Gao et al. 2020; Hasanzadeh et al. 2019; Ma et al. 2021; Sun et al. 2020). Toscano and Windau (1993) showed that about 90% of all injuries and accidents in the construction industry were accounted for by about 50% of workers. Clarke (2016) claimed that accidents are not distributed evenly and randomly across individuals, and individuals with certain personality traits are more accident-prone. Such accident proneness is highly correlated with an individual's ability to sustain attention or vigilance to workplace hazards (Cummings et al. 2016).

Researchers have adopted a number of personality inventories to identify associations between personality traits and unsafe behaviors: the Big Five Inventory (BFI), the Myers–Briggs Type Indicator (MBTI) inventory, and the Sensation Seeking Scale (SSS). Using the BFI, Hasanzadeh et al. (2019) demonstrated that introverted workers are more likely to be attentive to workplace hazards. Similarly, Gao et al. (2020), also using the BFI, observed a positive relationship between conscientiousness and construction workers' safe behaviors; the results indicate that individuals with high conscientiousness are less likely to engage in unsafe behaviors. The Sensation Seeking Scale is one of the most widely used measures of an individual's propensity to engage in risky behaviors (Zuckerman 2007). Sensation seeking is "a trait defined by the seeking of varied, novel, complex, and intense sensations and experiences, and the willingness to take physical, social, legal, and financial risks for the sake of such experience" (Zuckerman 2014, p. 11). Sensation seekers tend to underestimate risks or take a risk to achieve their goals (Zuckerman 1994). An individual's sensation-seeking can be measured by Zuckerman's self-report standardized scale, which consists of four subscales: Thrill and Adventure Seeking (TAS), Experience Seeking (ES), Disinhibition (Dis), and Boredom Susceptibility (BS) (Zuckerman 1994). Because high-scoring sensation seekers tend to take more risks than others, they may be more likely than others to become injured (Hasanzadeh et al. 2020a). Many studies have shown that a high score in sensation seeking is predictive of more reckless behaviors, including unsafe driving behaviors (Zuckerman 2007), adolescent health-risk behaviors (e.g., drinking and drug use) (Cestac et al. 2011), and military cadets' risk-taking behaviors (Breivik et al. 2015). Several studies in construction safety research also have attempted to explain the relationship between construction workers' sensation-seeking propensity and engagement in unsafe behaviors (Aroke et al. 2022; Ma et al. 2021; Sun et al. 2020). Collectively, these studies outline the need for safety training and interventions that consider individual differences in personality traits as essential human factors.

Boredom Susceptibility and Vigilance at Work

The association between sensation seeking and unsafe behaviors has highlighted the importance of understanding an individual's boredom susceptibility (Börjesson et al. 2011; Warm et al. 1998; Yakobi and Danckert 2021). Boredom susceptibility represents a low level of tolerance for routine work tasks or repetitive experiences (Zuckerman 1994). Therefore, among the four subdimensions of sensation seeking, boredom susceptibility is highly correlated with workers' inattention to workplace hazards (Cummings et al. 2016; Eastwood et al. 2012). Individuals with high boredom susceptibility tend to exhibit low vigilance—the ability to sustain attention to an external environment in order to respond to unpredictable events—while performing a work task (Cummings et al. 2016; Oxtoby et al. 2019; Shaw et al. 2010). Therefore, workers who tend to become more intensely and more frequently bored are more likely to engage in unsafe behaviors (Tam et al. 2021; Yakobi and Danckert 2021). Individuals with high levels of boredom susceptibility performed poorly in an experiment that measured the ability to sustain attention to an external environment (Hitchcock et al. 1999; Scerbo 1998). Kahn (1992) theorized that the vigilance of boredom-prone workers is apt to become depleted easily, and such boredom proneness may lead to workers' underestimation of risks associated with workplace hazards. Therefore, boredom-prone workers may be more vulnerable to safety-related injuries and accidents at work.

Human Behavior Analysis and Virtual Reality Environment

Recent developments in the field of virtual reality technology have led to a renewed interest in the analysis of human behavior using VR (Chittaro et al. 2018; Lin et al. 2020). A VR environment enables researchers to precisely control experimental variables that are hard to control in a real-world setting while recording participants' behaviors quantitatively and objectively without bias. Furthermore, in a VR environment, participants can be exposed to various types of workplace hazards without risking actual injuries. Several recent studies adopted VR to enhance construction safety by investigating construction workers' unsafe behaviors (Habibnezhad et al. 2020; Hasanzadeh et al. 2020b; Jeon and Cai 2021; Lu and Davis 2016; Shi et al. 2019; Jeelani et al. 2018). However, much uncertainty still exists about the relationship between construction workers' personality traits and their habituation tendency to warning alarms in road work zones.

Point of Departure and Research Hypotheses

Pedestrian workers in road work zones become less attentive to warning alarms that constantly beep across the work zones. Such inattention increases the risk of being struck by construction vehicles. Although studies have demonstrated a relationship between construction workers' personality traits and unsafe behaviors at work and have theorized that individual differences in sensation seeking can increase workers' engagement in injuries or accidents (Bhandari et al. 2021; Hasanzadeh et al. 2019; Sun et al. 2020), no study has empirically examined the role of personality traits in the likelihood of workers' accident involvement. Furthermore, although much psychology and human behavior research has linked individuals' boredom susceptibility with habituation at work (i.e., low levels of vigilance to workplace hazards), there still is very little scientific understanding of the effect of construction workers' boredom susceptibility on habituation to warning alarms from construction vehicles in road work zones.

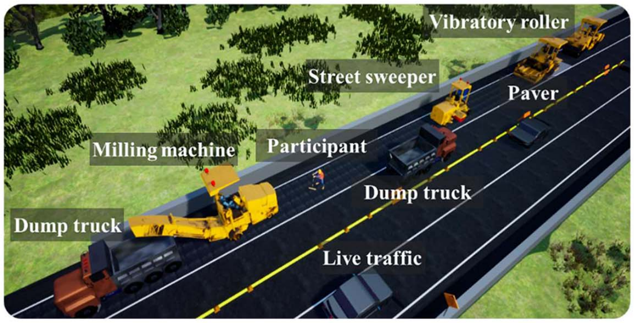
Direct observation enables an empirical analysis of human behavior, and assessing objective features of human behavior (e.g., latency, frequency, and intensity) plays an important role in analyzing individual differences in behavior patterns (Gresham et al. 2001). The frequency of human behavior is converted to a rate measure by dividing the number of exhibited target behaviors by the duration or number of exposures to a stimulus (Miltenberger and Weil 2013). The analysis of behavior rate is useful when an observation takes place multiple times (Gresham et al. 2001). In human behavior analysis, latency refers to the response time—the amount of elapsed time between an event and the onset of the target behavior (Kazdin 2019).

This study examined the association between sensation-seeking—specifically boredom susceptibility—and pedestrian workers' inattentiveness toward repeated warning alarms and engagement in struck-by accidents with construction vehicles by analyzing the frequency and latency of workers' behavioral responses to warning alarms in a virtual road construction environment. We anticipated that among the four subscales of sensation seeking, boredom susceptibility would have the strongest negative correlation with participants' checking behaviors elicited by warning alarms. Specifically, we performed an experiment with actual road construction workers and tested the following hypotheses:

Hypothesis 1: Pedestrian workers' boredom susceptibility is negatively correlated with the frequency of their vigilant behavior to repeated warning alarms from construction vehicles.

Hypothesis 2: Pedestrian workers' boredom susceptibility is negatively correlated with the latency of their attention to repeated warning alarms from construction vehicles.

Hypothesis 3: Pedestrian workers' boredom susceptibility is positively correlated with their likelihood of involvement in a struck-by accident during a construction task.



(a)

(b)

Fig. 2. Experimental environment: (a) overview scene of the immersive virtual road construction environment; and (b) participant's physical sweeping action synchronized in the virtual environment. (Reprinted from Kim et al. 2021a, © ASCE.)

Research Methods

The experiment was designed and performed with actual road construction workers to (1) investigate the impact of individual differences in boredom proneness on workers' habituation to repeated workplace hazards, and (2) examine the association between workers' boredom proneness and accident proneness. Thus, participants' behavioral responses toward repeated warning alarms associated with the risk of struck-by accidents were measured using a virtual road construction environment. The following sections describe the experimental environment, the measure of participants' personality traits, the experimental procedure, and the data analysis process.

Experimental Environment

Kim et al. (2021a) developed a VR environment that makes it possible to observe participants' vigilant behaviors in response to frequent warning alarms from construction vehicles. The experimental environment simulates a road work zone. In the virtual environment, a fleet of heavy construction vehicles, such as a milling machine, an asphalt paver, and dump trucks, continuously move close to a participant while presenting proximity warning alarms [Fig. 2(a)]. During the experiment, one of the vehicles, a street sweeper, travels behind a participant while making reciprocal back-and-forth movements. When the sweeper moves toward a participant, a warning alarm is presented. Then, when the distance between the sweeper and the participant reaches the designed minimum distance of 7.5 m, the warning alarm is turned off, and the sweeper starts to move backward. The volume of the warning alarm is designed to become louder as the sweeper moves closer to a participant and less loud as it moves away from a participant. Thus, a participant can be aware of the approaching sweeper based on the warning alarm. To effectively evoke habituated inattention to warning alarms, each participant was tasked with performing a road paving crew's task, sweeping out debris on the surface. Participants' sweeping action in the real world was captured and synchronized with hand movements in the virtual environment [Fig. 2(b)].

The virtual experimental environment also includes a function that simulates a struck-by accident with the sweeper if a participant does not exhibit vigilant checking behavior toward the sweeper. This function counts the number of times a participant looks at the approaching sweeper over the five most recent exposures to a warning alarm. If a participant ignores the warning alarm and neglects to look at the approaching sweeper more than three times during the five most recent exposures, the sweeper runs over the participant, and a first-person view of the accident is demonstrated. To obtain sufficient behavioral data from the experiment and to allow a participant to have sufficient time to be aware of the struck-by hazard associated with the proximity of the sweeper, the accident-triggering function is not activated until at least 10 exposures to the struck-by hazard. Three experienced safety managers at heavy and civil engineering construction companies reviewed the experimental scenario. The virtual road construction environment was built using Unreal Engine 4.22.3. The experiment used a Dell (Round Rock, Texas) Precision T5820 computer with an Intel i9-10900X 3.7 GHz CPU, 128 GB DDR4 RAM and Nvidia GeForce RTX 3080 GPU) and an HTC (New Taipei City, Taiwan) Vive Pro Eye with resolution of 2,880 × 1,600 pixels, field of view of 98° horizontal and 98° vertical and refresh rate of 90 Hz. Warning alarms were presented through the headset speakers.

Data Collection

Participants

Thirty-five road construction workers (32 males and 3 females) were recruited and participated in the experiment; their mean age was 27.26 years, with a standard deviation (SD) of 6.09. All participants were pedestrian workers employed by a heavy and civil engineering construction company in the US. Average years of work experience was 4.73 years ($SD_{exp} = 5.11$ years) with variation as follows (Table 1): less than 1 year (17.14%), 1 year to less than 5 years (51.42%), 5 years to less than 10 years (17.14%), 10 years less than 20 years (8.57%), and more than 20 years (5.71%). All participants had taken an Occupational Safety and Health Administration (OSHA) 10-h or 30-h training course. During the experiment, two participants felt motion sickness and dropped out of the experiment. Thus, data from 33 participants were used for the analysis. The experiment was performed based on the research protocol approved by the Institutional Review Board at Texas A&M University.

Table 1. Participants' working experience

Working experience (years)	*n*	Percentage
Less than 1	6	17.14
1 to less than 5	18	51.42
5 to less than 10	6	17.14
10 to less than 20	3	8.57
More than 20	2	5.71
Total	35	—

Personality: Measuring Sensation-Seeking Tendencies

To measure participants' sensation-seeking tendencies, Zuckerman's Sensation Seeking Scale Form V (SSS-V), a self-report, forced-choice questionnaire, was used (Zuckerman 1994). The scale includes 40 items; each item is formulated as two statements, and the participant must choose one of the two. The inventory measures four subdimensions of sensation-seeking. Examples of statement pairs include:

- "I often wish I could be a mountain climber." and "I cannot understand people who risk their necks climbing mountains."
- "A sensible person avoids activities that are dangerous." and "I sometimes like to do things that are a little frightening."
- "I would like to try parachute jumping." and "I would never want to try jumping out of a plane with or without a parachute."
- "I am not interested in experience for its own sake." and "I like to have new and exciting experiences and sensations even if they are a little frightening, unconventional, or illegal."

The total score ranges between 0 and 40, and the maximum score of each subscale is 10. Higher scores represent a greater tendency to seek sensation.

Vigilance to Warning Alarms: Measuring Behavioral Responses

In the experiment, participants' visual attention to the approaching sweeper was defined as "checking behavior"—moving their eyes to look at the approaching sweeper. The allocation of visual attention is crucial to comprehending surrounding environments, and visually checking the source of an alarm is an important safety behavior to avoid struck-by accidents associated with construction vehicles traveling in a work zone (Hoffman and Subramaniam 1995; Rensink et al. 1997). Thus, participants' visual attention to warning alarms from the sweeper was measured using eye-tracking sensors embedded in the HTC Vive Pro Eye. The eye-tracking sensors projected an invisible ray from a participant's gaze point and documented the names of objects that were hit by the invisible ray during the experiment, thereby indicating what a participant was looking at (Kim et al. 2021a; Seele et al. 2017). The duration of eye fixation is an indicator of human cognitive activities associated with visual attention allocation (Jiang et al. 2018; Strandvall 2009). In the human cognitive literature, 100 ms typically is considered as the lower threshold of eye fixation (Dupont et al. 2014; Inhoff and Radach 1998; Jacob and Karn 2003). During the experiment, if a participant gazed at the sweeper for more than 100 ms, it was counted as a hazard-checking behavior.

This study adopted two indexes—checking rate and checking distance—to evaluate participants' vigilance and habituation to warning alarms. The frequency of checking behaviors (i.e., checking rate) was documented. One reciprocal movement of the sweeper was defined as one exposure to the struck-by hazard. In each exposure, when a participant looked back to check the approaching sweeper, it was documented as a successful hazard check. Each participant's checking rate was calculated using the following equation:

$$\mathrm{CBR}_i = \frac{TC_{\mathrm{Success}}}{TE_{\mathrm{Total}}} \quad (1)$$

where TC_{Success} = a total number of successes in visually checking warning alarm by participant i; TE_{Total} = total number of exposures of participant i; and CBR_i = checking-behavior rate of participant i.

In this study, the latency of participants' behavior toward the warning alarm was reported by documenting the distance between a participant and the sweeper when the participant exhibited visual checking behavior for the first time after the warning alarm was presented at each exposure. To avoid data manipulation, if a participant did not exhibit visual checking behavior until the sweeper reached the designated minimum distance at which the sweeper started to move in reverse, that exposure was excluded from the analysis of latency of behavioral responses and was included only in the analysis of the frequency of behavioral responses (Kim et al. 2021a).

Experimental Procedure

The experiment was performed in a safety training room of the company. Before commencing the experiment, participants signed the consent form and were requested to fill out the sensation seeking survey. Each participant completed a practice session to learn how to perform the assigned sweeping task in the virtual environment. During the practice session, warning alarms were not presented, and the construction vehicles were not moving. During the experiment, participants were asked to (1) sweep out all debris on the surface of the working lane, (2) follow the asphalt milling machine, and (3) pay attention to warning alarms for safety purposes. Some participants were involved in a virtual accident. When a virtual accident was triggered, the experiment was terminated. Otherwise, the experiment was terminated after 20 min. The experiment took about 1 h/participant, including the VR practice session and other pretest surveys.

Data Analysis and Hypothesis Testing

All analyses were performed using RStudio version 1.2.5. Prior to hypothesis testing, to evaluate the internal consistency of all sensation seeking subscales, Cronbach's alpha values were computed. Then a hierarchical multiple regression analysis was performed to examine whether demographic variables (e.g., age, working experience, and VR familiarity) were associated with participants' warning alarm checking behaviors during the experiment.

To test Hypothesis 1 regarding the association between sensation seeking and the frequency of attentive behavior toward repeated warning alarms, correlation analysis and bivariate linear regression analysis were performed. The bivariate linear regression model predicting checking-behavior rate and the score of boredom susceptibility used the following equation:

$$\widehat{y}_i = B_0 + B_1 S + r \quad (2)$$

where $\widehat{y}_i$ = checking-behavior rate at each level of boredom susceptibility S; B_0 = intercept of regression line at $S = 0$; and B_1 = slope of regression that indicates change in checking-behavior rate $\widehat{y}_i$ for each 1-point increase in boredom susceptibility. If the test result of coefficient B_1 is significantly negative, the association between participants' boredom susceptibility and their vulnerability to inattentiveness toward repeated alarms can be determined.

Hypothesis 2 was tested using multilevel modeling (MLM) analysis. A two-level MLM analysis was performed to examine the relationship between the variances in the within-participant level predictor (i.e., exposure time) to warning alarms and the variances in the between-participant level predictor (i.e., boredom susceptibility). In this study, a variable on the first level of the model (within-participant level) was exposure time. The second level (between-participant level) variable was the boredom susceptibility of each participant. The total number of observations for exposure time at the first level is nested within a participant at the second level (i.e., a level-2 dimension). Because boredom susceptibility was calculated only one time per participant, boredom susceptibility was modeled as a participant-level predictor. The following equations were used for MLM analysis:

- Level 1: Within-participant level model

$$y_{ij} = B_{0j} + B_{1j}T_{ij} + B_{2j}S_{ij} + B_{3j}[T \times S_{ij}] + r_{ij} \quad (3)$$

where y_{ij} = sum of participant intercept; j = participant ($j = 1, 2, 3, \ldots, n$); i = observation ($i = 1, 2, 3, \ldots, n$) within a participant's session; B_{0j} = intercept in participant j; B_{1j} = slope that represents predicted decrease in checking distance by 1-min increase in exposure time T of participant j; B_{2j} = slope that represents predicted change in checking distance with 1-point increase in boredom susceptibility S; and B_{3j} = slope of interaction term of exposure time T and boredom susceptibility S.
- Level 2: Between-subject level model

The intercept of the participant level is

$$B_{0j} = \gamma_{00} + \gamma_{01}S_j + \upsilon_{0j} \quad (4)$$

where S_j = boredom susceptibility of participant j; γ = regression coefficient at participant level; γ_{00} = intercept over participant when all predictors are zero; γ_{01} = intercept of boredom susceptibility S of participant j; and υ_{0j} = participant-level error in intercept. The slope of the participant level is

$$B_{1j} = \gamma_{10} + \gamma_{11}S_j + \upsilon_{1j} \quad (5)$$

where γ_{10} = slope of participant; γ_{11} = regression coefficient of boredom susceptibility S; and υ_{1j} = participant-level error in slope. Eqs. (3)–(5) were integrated into Eq. (6). The MLM analysis was performed using the lme4 module of R (Bates et al. 2014). As the continuous variable, exposure time T was scaled and mean-centered

$$y_{ij} = (\gamma_{11}S_j + \gamma_{10} + \upsilon_{1j})T_{ij} + (\gamma_{01}S_j + \gamma_{00} + \upsilon_{0j}) + r_{ij} \quad (6)$$

The result of the significance test for the MLM model indicates how differences in boredom susceptibility was correlated with a decrease in checking distance.

A bivariate logistic regression was computed to test Hypothesis 3. The predictor variable was boredom susceptibility, and the dependent variable was participants' involvement in a virtual accident during the experiment. A participant's involvement in a virtual accident was added as a dichotomous variable (dummy-coded: 0 = no accident, 1 = accident)

$$\ln\left(\frac{\hat{p}}{1-\hat{p}}\right) = B_0 + B_1 S \quad (7)$$

where $\hat{p}$ = estimated probability of virtual accident occurring during experiment; B_0 = log odds of score of boredom susceptibility in accident group for $S = 0$; and B_1 = change in log odds of score of boredom susceptibility in accident group with a 1-unit increase in S.

Results

Reliability and Correlations

The internal consistency for all sensation-seeking subdimensions—Thrill and Adventure Seeking, Experience Seeking, Disinhibition, and Boredom Susceptibility—was confirmed by computing Cronbach's alpha coefficients. When Cronbach's alpha is 0.70 or above for each subscale, the scales are considered to be internally consistent (Taber 2018). Although Cronbach's alpha coefficient of TAS ($\alpha = 0.69$) was less than 0.70, it was marginally acceptable. Cronbach's alpha value of the other subdimensions reached an acceptable level: ES ($\alpha = 0.75$), Dis ($\alpha = 0.72$), and BS ($\alpha = 0.79$).

Table 2. Hierarchical regression coefficients for checking-behavior rate

Predictors	β	Standard error (SE)	t-value	p-value	R^2	ΔR^2	F
Step 1	—	—	—	—	0.048	0.048	0.488
Age	−0.142	0.015	−0.916	0.368	—	—	—
Working experience	0.000	0.021	0.011	0.992	—	—	—
VR familiarity	−0.032	0.059	−0.543	0.592	—	—	—
Step 2	—	—	—	—	0.447	0.399	2.883*
TAS	−0.036	0.032	−1.124	0.272	—	—	—
ES	−0.022	0.032	−0.674	0.506	—	—	—
Dis	0.048	0.033	1.456	0.158	—	—	—
BS	−0.126	0.033	−3.869	<0.001**	—	—	—

Note: TAS = thrill and adventure seeking; ES = experience seeking; Dis = disinhibition; and BS = boredom susceptibility. *Significant at $p = 0.05$ level; and **significant at $p = 0.01$ level.

A two-step hierarchical multiple regression analysis was conducted to examine the effect of demographic factors (e.g., age, working experience, and VR familiarity) on checking-behavior rate. Table 2 presents the regression coefficients for every variable at each step of the model. In the first step, age, working experience, and VR familiarity were entered as covariates. The prediction at this step of the model was not significant [$R^2 = 0.05$, $F(3, 29) = 0.49$, $p = 0.69$], and none of the predictors evidenced an independent predictive association with the checking-behavior rate. In the second step of the model, four subdimensions of sensation seeking (TAS, ES, Dis, and BS) were entered to evaluate their associations with checking-behavior rate. The addition of these predictors accounted for a significant proportion of the variance in checking-behavior rate [$\Delta R^2 = 0.40$, $F(7, 25) = 2.88$, $p < 0.001$]. At this step of the model, BS ($\beta = -0.13$, $p < 0.001$) contributed significantly to the prediction of checking-behavior rate, whereas other subdimensions of sensation seeking—TAS, ES, and Dis—were not predictive of checking-behavior rate.

Hypothesis 1 Testing

Bivariate correlations were computed between each of the subdimensions of sensation seeking and participants' checking-behavior rate during the experiment (Table 3). Although the result revealed that checking-behavior rate was negatively correlated with all four subdimensions of sensation seeking, only boredom susceptibility was significantly correlated with checking-behavior rate ($r = -0.499$, $p < 0.01$). The correlations between the checking-behavior rate and other subdimensions of sensation seeking—TAS, ES, and Dis—were nonsignificant.

Hypothesis 1 was confirmed by testing the bivariate regression model predicting checking-behavior rate from the boredom susceptibility score. Although the association between the total score of sensation-seeking and checking-behavior rate was not significant [$R^2 = 0.11$, $F(1, 31) = 3.75$, $p = 0.062$], the association between the boredom susceptibility score and the checking-behavior rate was significant (Fig. 3) [$R^2 = 0.29$, $F(1, 31) = 12.85$, $p < 0.01$]. The boredom susceptibility score negatively predicted checking-behavior rate ($B_1 = -0.11$, $p < 0.01$). The result indicates that the frequency of participants' behaviors to check warning alarms from the construction vehicle decreased with the increase of participants' boredom susceptibility scores.

Table 3. Correlations between sensation seeking subdimensions and checking-behavior rate

	Correlation				
Variable	1	2	3	4	5
1. Checking-behavior rate	1.000	—	—	—	—
2. TAS	−0.114	1.000	—	—	—
3. ES	−0.132	0.522**	1.000	—	—
4. Dis	−0.030	0.358*	0.293	1.000	—
5. BS	−0.493**	0.131	0.035	0.186	1.000

Note: TAS = thrill and adventure seeking; ES = experience seeking; Dis = disinhibition; and BS = boredom susceptibility. *Significant at $p = 0.05$ level; and **significant at $p = 0.01$ level.

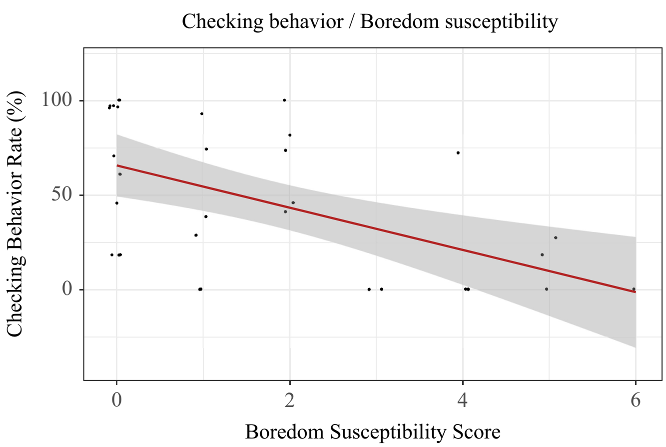


Fig. 3. Checking-behavior rate plotted as a function of boredom susceptibility, which is a subdimension of sensation seeking. The data are jittered to prevent overlapping dots.

Hypothesis 2 Testing

To investigate how the individual differences in boredom susceptibility scores affect participants' habituation to warning alarms, MLM analysis was performed. In the MLM analysis, the total number of observations (i.e., sample data points) was 371. The results of MLM analysis are presented in Table 4. Coefficient B_1, exposure time, approached significance ($p = 0.075$), and coefficient B_3, the interaction of exposure time and boredom susceptibility, was significant ($p = 0.041$). The results indicate that participants with higher boredom susceptibility scores tended to habituate more quickly to warning alarms as a function of exposure time than did participants with lower boredom susceptibility scores.

Fig. 4 shows the difference in checking distance between participants with different boredom susceptibility scores. The slope of each line indicates the effect of boredom susceptibility (between-participant level predictor) on the strength of the relation between checking distance and exposure time (within-participant level predictor) at the mean for the boredom susceptibility score, 1 standard deviation above the mean boredom susceptibility score, and 1 standard deviation below the mean boredom susceptibility score.

Hypothesis 3 Testing

During the experiment, 21 of 33 participants experienced a VR accident, and 12 participants did not experience the VR accident because they maintained a consistent level of vigilance to warning alarms and checked the approaching vehicle regularly. Hypothesis 3 was confirmed through logistic regression analysis. The model was significant ($\chi^2 = 5.2$, $p = 0.023$). The model explained 27.6% (Nagelkerke R^2) of the variance in the VR accident occurrence and correctly classified 72.7% of VR accident occurrence. As the boredom susceptibility score increased by 1 point, the odds of a VR accident were multiplied by 1.92 {odds ratio = 1.92, 95% confidence interval (CI) [1.18, 3.79]}. This result indicates that an increase in the boredom susceptibility score was associated with an increased likelihood of a VR accident.

Discussion

There are a number of possible explanations for construction workers' habituation to workplace hazards. Anecdotal evidence indicates that workers with certain personality traits (such as extraversion and being prone to sensation seeking) tend to be more inattentive at work than other workers (Beus et al. 2015; Hogan and Foster 2013). Consequently, they are more likely to be involved in injuries or accidents. Most studies of the association between workers' sensation seeking propensity and their unsafe behaviors at work mainly explained this association using the total score of the Sensation Seeking Scale, which is the sum of the four subdimension scores. However, our findings indicate that workers' boredom susceptibility is the one subdimension that best explains an individual's vulnerability to habituation to warning alarms from construction vehicles. A possible explanation for this result could be an association between boredom proneness and vulnerability to alarm fatigue, which has been discussed widely in human factors research (e.g., Cummings et al. 2016; Solet and Barach 2012).

Our results broadly support the work of psychology studies that link individuals' boredom susceptibility with sustained attention to an external environment (Shaw et al. 2010; Whiteoak and Mohamed 2016; Yakobi and Danckert 2021). The frequency of hazard-checking behavior decreased with an increase in the boredom susceptibility score. Furthermore, the latency of participants' hazard-checking behaviors decayed over time, and the habituation pattern for workers prone to boredom was significantly faster than it was for others with lower boredom susceptibility scores. During debriefing, participants who were involved in a virtual accident said they focused mainly on the sweeping task after several warning alarms because they started to think that the vehicle made a cyclic

Table 4. Fixed effects of multilevel model on checking distance of exposure time and boredom susceptibility

Predictor	Estimate	SE	95% CI	t-value	p-value
B_0 intercept	1,779.67	107.70	(1,568.58, 1,990.76)	16.52	<0.001**
B_1 exposure time	−12.15	6.82	(−25.52, 1.22)	−1.78	0.075*
B_2 BS	−24.63	62.96	(−148.03, 98.77)	0.39	0.696
B_3 exposure time × BS	−10.34	5.07	(−20.27, −0.41)	−2.04	0.041*

Note: BS = boredom susceptibility. *Significant at $p = 0.05$ level; and **significant at $p = 0.01$ level.

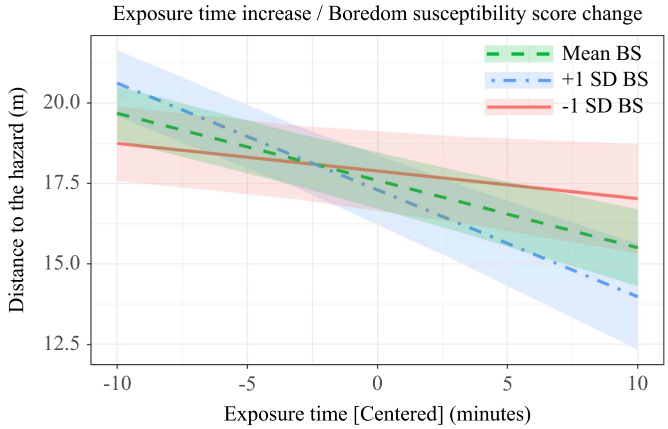


Fig. 4. Slopes for the effect of exposure time (centered at the mean) on checking distance at the mean boredom susceptibility score, 1 standard deviation above the mean boredom susceptibility score, and 1 standard deviation below the mean boredom susceptibility score.

movement and would not hurt them. Participants' explanations imply that the experimental design of this study effectively evoked their habituated inattention to alarms from construction vehicles.

Whereas most studies used indirect methods to determine an association between construction workers' personality traits and unsafe behaviors or accident involvement, our study directly tested these associations. Other studies typically collected information on accident involvement through participants' self-reporting of unsafe or inattentive behaviors at work (Clarke and Robertson 2005; Ma et al. 2021), and inferred accident proneness from construction workers' hazard recognition skills (Aroke et al. 2022; Hasanzadeh et al. 2019), and then assessed the association between personality with the result of those measures. However, this study exposed participants to a virtual road construction environment and observed their likelihood of being involved in an accident (e.g., being struck by a truck), and then assessed the association between participants' personality traits and accident proneness. Due to memory decay and reluctance to expose private information, construction workers' self-reporting of their prior injuries and accidents may have limited reliability. Therefore, the findings of this study may be more generalizable to behavior in real-world work zones.

Another contribution of this study is that it is the first to directly assess the relationship between construction workers' personality traits and habituation to warning alarms in a road construction context. Specifically, participants' physical behaviors were synchronized with behaviors in a virtual environment, thus enabling a direct assessment of associations between construction workers' personality and their responses to warning alarms. To make the virtual environment more immersive, the warning alarms presented were extracted from real-world alarm sounds—backing-up beep sounds of dump trucks and other construction vehicles. Due to such vividness of the simulated virtual road construction environment, participants' performance in this study enabled us to investigate pedestrian workers' habituation to warning alarms. Finally, personality is known to be associated with advanced psychological processes (e.g., emotion, motivation, and decision making), and it influences the way a person thinks, lives, and gets along with others, whereas habituation is a concept that is linked more tightly to lower-level cognitive processes (e.g., sensory and perception), and it influences how a person experiences the physical attributes of stimuli. Thus, it was meaningful and original for this study to investigate the possible relationship between these two seemingly disparate psychological domains, and the significant correlation between personality and habituation to warning alarms we observed may indicate that there are certain underlying mechanisms that can link higher-level cognitive processes with lower-level sensory processes.

Because the findings of this study demonstrate associations between pedestrian workers' boredom susceptibility and habituation to proximal warning alarms from construction vehicles, we can conclude that some workers are more vulnerable to struck-by accidents in road work zones, likely because of their habituation to the proximity warning alarms from construction vehicles. Thus it can be suggested that conventional safety training, with a one-size-fits-all approach, should consider incorporating individual differences in personality traits. The findings of this study could better prevent workers' habituated inattention to constant warning alarms at road work zones by motivating tailored safety training that reflects individual workers' personality traits. Safety practitioners could indicate to workers how individuals' boredom proneness is associated with vulnerability to habituation which may result in negative consequences such as accidents and injuries, thereby motivating workers to become more conscious about how they process workplace hazards. Our findings also provide a conceptual basis for identifying higher-risk employees for enhanced trainings that might not be logistically feasible for all employees to complete, including VR training such as that implemented in this study.

Several limitations of this study should be noted. First, although other personality inventories have been adopted widely in the assessment and analysis of individuals' personalities (e.g., Big Five inventory, Myers–Briggs type indicator, and Locus of Control), this study measured workers' sensation-seeking propensity using only the Sensation Seeking Scale. A future study could combine other personality inventories to uncover a richer complexion of personality traits that best explains individuals' vulnerability to habituation to warning alarms. Second, the scope of this study was limited to workers' habituation to struck-by hazards in road work zones associated with warning alarms from construction vehicles, and did not consider other types of workplace hazards, such as fall hazards, caught-in or caught-between hazards, and electrocution hazards, which may require different experimental approaches. Different construction tasks require different safety behaviors, requiring specific abilities and skills (Glendon and Clarke 2015; Lawton and Parker 1998). Therefore, further validation is needed with respect to workers' habituation tendency to various types of workplace hazards. Third, the virtual struck-by accident in our experiment was triggered when a participant failed to check on the approaching vehicle in three of the five most recent exposures. This trigger was arbitrary to some degree. However, a worker's frequent ignorance of the repeated alarm is an important indicator of the likelihood of involvement in runover or backover accidents in road work zones, which was reflected in our experiment design (Daalmans and Daalmans 2012; Pegula 2013). Last, although this study was performed with 35 actual pedestrian workers, further experiments with larger and more-diverse samples are an essential next step. In this study, only about 9% of participants, (3 participants) were female, and more than 90% of participants (32 participants) were male. This imbalanced gender ratio could be due to the gender imbalance observed in the construction industry. According to the National Center for Health Statistics, at least 90% of construction workers in the US are males (Brown et al. 2021). Thus, from a gender perspective, our sample is representative of the population of construction workers in the US. In spite of such limitations, this study adds to the understanding of the human factors affecting construction workers' habituated inattention to warning alarms from construction vehicles and their involvement in struck-by accidents in road work zones.

Conclusion

This study was designed to empirically investigate the role of personality traits in road construction workers' tendency to become habituated to repeated auditory alarms from construction vehicles. The effect of individual differences in boredom proneness on workers' accident proneness was examined using a virtual reality environment. The results reveal that boredom susceptibility, one of the subdimensions of sensation seeking, is negatively correlated with workers' attention to warning alarms. An individual's boredom susceptibility score also significantly predicted the likelihood of being involved in a virtual runover accident. These findings suggest that workers who have a tendency to become bored more easily in daily life are more likely to be inattentive to warning alarms from construction vehicles in road work zones. The results also broadly support the work of psychology studies linking individuals' boredom susceptibility with habituation to surrounding environments. The findings of this study advance the understanding of workers' habituated inattention to warning alarms from construction vehicles in road work zones, thereby contributing to effective struck-by accident prevention strategies in road work zones. Furthermore, the assessment of workers' personality traits would allow workers to be aware of their individual vulnerability to accidents in construction sites, which could promote attentiveness to frequently encountered workplace hazards.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request.

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