# The Impact of Intrapersonal and Environmental Visual Impairment on Pedestrian Safety

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## Authorization to Submit Dissertation

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# Abstract

Each year more than 140,000 adult pedestrians are struck by motor vehicles, resulting in heavy costs of both life and economy. Research has endeavored to investigate the etiology of pedestrian injury for decades. Recently a need has been identified – and begun to be addressed – for empirical work systematically examining the roles of vision and audition in various components in the pedestrian task. I designed and carried out two studies with the overall aim of investigating how safety is impacted if a pedestrian's perception is impaired on a sensory level rather than, for example, via distraction. Specifically, I conducted one study to examine the intrapersonal visual perceptual impairments introduced by alcohol intoxication, and another study to examine environmental sources of visual occlusion. The aforementioned intrapersonal and environmental sources of impairment were examined across two important components of the pedestrian task, time-to-contact estimations and gap selections. Secondary constructs known to be associated with one or both types of impairment were also be examined, including visuospatial performance, visual acuity, and contrast sensitivity. Alcohol intoxication negatively impacted time-to-contact judgment accuracy; no other significant effects of either intrapersonal or environment visual impairment emerged. I discuss my findings in terms of their implications for pedestrian safety research and for injury prevention efforts and conclude with considerations for future research.

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# Dedication

Dedicated to my mother and father, Ria and Phillip Davis.

In loving memory of my grandmother, Cecelia Puglisi.

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# Chapter 1: Introduction

Crossing a street is a complex task comprising several steps (Thomson, Tolmie, Foot, & McLaren, 1996). A pedestrian must detect the presence of traffic, judge whether a crossing location is safe in terms of factors such as traffic volume and visibility, and determine whether enough time is available for crossing before making a final decision. Unfortunately, and unsurprisingly, the danger and complexity inherent to the pedestrian task render injury an all-too-common event. In 2015 alone, approximately 4,800 adult pedestrians aged 18 or older died due to collision with a motor vehicle in the United States and more than 139,000 received non-fatal injuries requiring medical attention (National Center for Injury Prevention and Control, 2017). On a global scale, pedestrians comprised 22% of the 1.25 million road traffic deaths in 2013, with the highest proportion in the African Region (World Health Organization, 2013). Overall, pedestrian injury is a common form of unintentional injury, resulting in multidisciplinary attention toward injury prevention and identification of risk factors for pedestrian injury.

A variety of disciplines have endeavored to increase pedestrian safety.  Engineering, for instance, has concentrated on creating and implementing injury prevention measures via roadway design. The Manual of Uniform Traffic Control Devices contains specifications for the design and implementation of traffic control devices such as countdown signals and road signage (Federal Highway Administration, 2012). While such engineering solutions for pedestrian safety are valuable, police accident reports indicate pedestrians involved in collisions with vehicles often exhibit behaviors such as disregarding traffic signals (Ulfarsson, Kim, & Booth, 2010). Therefore, special consideration of human cognition, perception, and behavior is also necessary for a thorough examination of the antecedents of pedestrian injury.

Many risk factors for pedestrian safety have been identified. Some risk factors lie within the environment. For example, pedestrian injury rates are particularly likely to occur areas with high traffic volume, high population density, a high proportion of males, a high degree of unemployment, a low proportion of well-educated residents, and/or a high density of bars (Guth, Ashmead, Long, Wall, & Ponchillia, 2005; Lascala, Gerber, & Gruenewald, 1999). Other risk factors are intrapersonal, such as personality (Schwebel, Stavrinos, & Kongable, 2009), perceived behavioral control (Barton, Kologi, & Siron, 2016), sex-stereotype conformity (Granié, 2009), and age (Lobjois & Cavallo, 2007; Oxley & Fildes, 1999). However, the risk factors most relevant to the present paper are those which are related to visual perception – the biopsychological processes pedestrians use to glean visual information about their surroundings and ultimately make a crossing decision.

Visual perception is an often-studied factor which plays a vital role in pedestrian safety. The importance of vision in the pedestrian context is readily demonstrated by children traditionally being taught to look both ways before crossing a street. When visibility is obstructed, whether due to environmental factors (e.g., a hill or parked car) or the pedestrian's own sensory impairment (Barlow, Bentzen, & Bond, 2005), the risk of pedestrian injury increases due to a heightened reliance on auditory cues and a lack of visual information about oncoming traffic. Even individuals with visual sensory impairments who are experienced in using auditory cues to inform their crossing decisions are disadvantaged by their inability to nonverbally (i.e., visually) communicate with drivers (Ashmead et al., 2005).

While the overall impact of visual impairment on pedestrian safety is relatively clear, less is known about the mechanisms by which visual impairment interferes with the pedestrian task and which component(s) of the pedestrian task are most heavily impacted. I conducted two studies to examine several stages of the pedestrian task in the context of various forms of visual perceptual impairment, both intrapersonal and environmental. Before describing pedestrian visual perception and the studies in more detail, I will first discuss the literature related to pedestrian perceptual skills in general. Specifically, I will begin with a general overview of the importance of audition and vision in the pedestrian task, followed by brief coverage of the developing body of literature examining pedestrian audition. I will then shift focus to pedestrian visual perception, with an emphasis on salient skills and risk factors such as attention and distraction respectively. Next, I will describe two key components of the pedestrian task, time-to-contact estimation and gap selection, in the context of visual perception. Finally, I will describe visual perception-related risk factors that to my knowledge have not yet been adequately studied in a pedestrian context, namely alcohol intoxication and occlusion through fog or parked vehicles, thereby laying the foundation for two studies.

## Perceptual Skills in the Pedestrian Task

Vision and audition are both important for pedestrians. Whether in a crosswalk or any other context, a person’s perception of the environment emerges from the integration of sensory signals both between and within modalities such as vision, audition, and even the vestibular system in a bottom-up process that weights modality-specific cues according to reliability (Ernst & Banks, 2002; Fetsch, DeAngelis, & Angelaki, 2010; Toscano & McMurray, 2010). The pedestrian task involves using perceptual information to orient one’s attention toward salient environmental features such as vehicles and traffic control devices, judge speeds and distances of approaching vehicles, estimate time to vehicular contact, and determine viable crossing opportunities (Barton, 2006; Demetre et al., 1992; Lee et al., 1984). Visual perception is useful throughout the pedestrian task, and while the present paper predominantly focuses on visual perception, the importance and utility of audition in the pedestrian task should be acknowledged. Research suggests the bottom-up process of weighting sensory cues may be modulated via top-down attention orientation (Rohe & Noppeny, 2018), a phenomenon which may increase the importance of audition in situations where a pedestrian's access to visual environmental information is impaired or otherwise unavailable.

## Audition

Some recent research has begun to examine the role of auditory cues (specifically vehicle noises) in pedestrian safety. An early investigation found a significant relationship between vehicle speed and pedestrians’ performance in detecting approaching vehicle noises (Barton, Ulrich, & Lew, 2012). Detection distance was positively correlated with vehicle speed: Faster-moving vehicle noises were detectable at greater distances than noises from slower-moving vehicles, likely due to the louder noise signatures inherent to higher vehicle speeds. Follow-up study investigated developmental differences in auditory vehicle detection (Barton, Heath, & Lew, 2015; Barton, Lew, Kovesdi, Cottrell, & Ulrich, 2013). Generally, detection performance improved with age: Adults and older children detect approaching vehicles more quickly than younger children (< 10 yrs.), and older adults detect vehicles at even greater distances than younger adults.

The utility of audition appears to be diminished in situations with increased auditory complexity. The presence of a secondary vehicle or even background traffic noise can interfere with a pedestrian's ability to detect vehicles at safe distances and determine vehicle travel paths, resulting in greater injury risk (Ashmead et al., 2012; Emerson & Sauerburger, 2008; Ulrich, Barton, & Lew, 2014). Engagement in a secondary task, such as a vocal cell phone conversation, also negatively impacts pedestrian performance in vehicle noise detection and judgments of safe vehicle distances for crossing (Davis & Barton, 2017). Given the apparent volatility of pedestrian performance when reliant on auditory cues, a need exists to better understand the respective roles, strengths, and weaknesses of audition and vision in various parts of the pedestrian task for the sake of informing injury prevention efforts.

To my knowledge, only a single study has systematically compared the relative utilities of vision and audition in any component of the pedestrian task. Specifically, a series of two experiments used a prediction motion task to examine how participants' judgments of vehicular time-to-contact in a virtual environment differed according to perceptual modality (Pugliese, Barton, Davis, & Lopez, 2019). Time-to-contact estimations were significantly less accurate in the auditory-only condition compared to the visual-only condition or the naturalistic mixed-modality condition, and the effect was stronger when ambient background traffic noise was present. Moreover, participants' performance did not significantly differ between the visual-only and mixed-modality conditions. Overall, the results suggest vision is more useful (and therefore ostensibly more important) than audition for the portion of the pedestrian task corresponding to estimating the time-to-contact of an approaching vehicle.

In addition to investigating the roles of vision and audition in various portions of the pedestrian task, a need also exists to examine how each modality may uniquely be impaired as well as the implications of modality-specific impairment. A recent review paper highlighted the importance of empirically examining each modality independently in the context of pedestrian safety (Davis, Pugliese, & Barton, 2019). Independent consideration of vision and audition, including independent consideration of how each modality may uniquely be impacted (perhaps even impaired) by external factors, constitutes an important step toward achieving a better scientific understanding of each modality's role in the pedestrian task – and ultimately, more effective injury prevention practices. The present studies focused on visual perception, so I will now discuss literature relevant to pedestrian visual perception.

## Vision

Visual perception, compared to auditory perception, is overall much more widely acknowledged as a crucial skill in the pedestrian task. The practice of teaching children to look both ways before crossing the street is one example of how vision's role is recognized even among the general population. Scientific pedestrian safety research has also historically studied pedestrian visual perception. Some research has studied visual perception explicitly, such as one study which examined the ability of low-vision pedestrians to perceive countdown-style crosswalk signals (DeLaere, Houten, Morgan, & Shurbutt, 2015). Other studies have investigated visual perception more tacitly. Such studies might, for example, examine processes or task components in the context of factors that can impact visual perception, such as distraction via a secondary task.

Indeed, distraction via a secondary task is a major way visual perception may be impeded. Mobile devices such as cell phones present a common and ecologically valid example of a distractor, leading to much attention toward the issue in the pedestrian safety literature (see Stavrinos, Pope, Shen, & Schwebel, 2018, for a review). Interestingly, visually demanding distractors (such as texting) seem to impact pedestrians in a similar fashion as cognitively demanding distractors (such as a cognitively complex phone conversation).

Specifically, both types of distraction resulted in distracted pedestrians waiting longer, crossing more slowly, and missing more crossing opportunities.

**Attention.** Visual perception's importance to pedestrian safety extends beyond just the impact of distraction. A pedestrian's selective attention, especially the process of attention orientation, heavily involves vision (Barton, 2006). Specifically, vision plays an important role in cuing a pedestrian to attend to salient stimuli (such as oncoming traffic), as well as for detecting the presence of vehicle(s) in the first place. While foveal vision is generally understood to be more quick and acute for hazard detection than peripheral vision, pedestrians have been found to be able to detect hazards such as approaching vehicles using peripheral vision as well (David, Foot, & Chapman, 1990). From a developmental perspective, visual acuity – especially peripheral vision – is generally lower in children. Specifically, the retina as well as areas of the visual cortex responsible for processing peripheral stimuli are underdeveloped in young children around age 5 (Beazley, Illingworth, Jahn, & Greer, 1980; Kovacs, Kozma, Feher, & Benedek, 1999). As a result, young children are at heightened risk compared to older children and adults for failing to perceive salient stimuli (such as vehicles) in the road environment (David, Foot, Chapman, & Sheehy, 1986).

Cognitive load plays a role in attention orientation as well. According to Multiple Resource Theory, perception and cognition share a pool of mental resources (Wickens, 2002). To be clear, sharing mental resources does not imply the two processes to be synonymous – rather, tasks relying heavily on one or the other will draw from a shared figurative "pool" of attentional resources, leading to potential dual-tasking costs. Therefore, increased cognitive load should have negative effects on the performance of a perceptual task (such as vehicle detection). Recent empirical evidence suggests such a relationship between perception and cognition (Murphy & Greene, 2017). Specifically, participants' ability to suppress distracting stimuli in a visual search task was diminished when under high cognitive load. In other words, participants were more likely to allocate attention to distractors when under high cognitive load. Similar results have been found in a pedestrian context, with lower visual search performance observed in individuals with lower visuospatial working memory capacity, measured via the Corsi Block Task (Kovesdi & Barton, 2013). Taken together, working memory seems to be a particularly important component of cognition in the context of attention orientation (Lavie & De Fockert, 2005), specifically in that working memory facilitates allocation of attention to salient stimuli. More research is necessary to understand the relationship between cognition and other components of the pedestrian task, especially given the relationship between low working memory capacity and potentially hazardous behaviors such as mind wandering (McVay & Kane, 2009; Robinson & Unsworth, 2015).

## Time-to-Contact & Gap Selections

According to Thomson et al. (1996), the processes of vehicle detection and attention orientation are shortly followed by an estimation of how much time remains until the vehicle reaches the crosswalk (or more generally, the pedestrian's planned crossing path). The goal of this stage of the pedestrian’s task may be described, at least in part, as estimating whether enough time is available for safe crossing by observing vehicular movement. This estimate has been interchangeably referred to under several names throughout the literature, including time-to-contact, time-to-arrival, time-to-passage, time-to-coincidence and time-to-collision (Hancock & Manser, 1998). However, each of these terms have specific definitions in other domains. For example, time-to-contact involves a stationary observer and a moving object; time-to-arrival involves a moving observer and a stationary object; and time-to-collision involves both a moving observer and a moving object. Under this taxonomy, time-to-contact most closely encapsulates the road environment from the pedestrian's perspective and will therefore be the term of choice for the remainder of this paper.

Time-to-contact can theoretically be estimated in at least two ways. First, the estimated distance of the moving object (in this case a vehicle) can be divided by the object's estimated speed to yield the object's estimated time-to-contact. Another, more automatic, method of estimation involves a concept called tau (Lee, 1976). Tau is the ratio of the angular separation between two given retinal image points on the given object and the rate of separation of those two points. Put differently, tau is an estimate of time-to-contact based on a person's perceived rate of change of the optic array. Here, too, we see the utility of vision in pedestrian safety: Time-to-contact can be estimated in the absence of any environmental cues other than expanding images in the visual field (Schiff & Detwiler, 1979). Further, some research with pedestrian virtual reality simulators suggests the presence of auditory perceptual cues does not impact the accuracy of time to arrival estimations when visual information is available (Pugliese, Barton, Davis, & Lopez, 2019).

Important to note, however, is that a pedestrian's time-to-contact estimate is not always accurate, nor does the estimate perfectly predict an actual crossing attempt. Relatively early perceptual transportation safety research using two-dimensional simulators (e.g., Manser & Hancock, 1996; McLeod & Ross, 1983) found participants generally underestimated time-to-contact. Further research using “pretend roads” has shown pedestrians may be even more conservative and cautious when making an actual crossing decision versus when simply judging time-to-contact (e.g., Demetre et al., 1992; Te Velde, van der Kamp et al., 2005). In other words, while pedestrians *can* make time-to-contact estimations of approaching vehicles using visual information, the estimations are usually conservative and not necessarily accurate, especially when an estimation is to be followed by an actual crossing. Therefore, the imperfect correlation between perceptual judgments and action execution must be carefully considered in pedestrian safety research. Simply studying pedestrian time-to-contact estimations is not enough and should be supplemented by consideration of the eventual coordination of perception and action.

After perceiving traffic, a pedestrian must select a crossing opportunity. Specifically, the pedestrian must select a gap in traffic that affords enough time to safely cross the street. In other words, the vehicle's time-to-contact must exceed the time necessary for the pedestrian to cross. Traffic gap selection has been the subject of scientific inquiry using sighted, blind, as well as low-vision pedestrians (e.g., Demetre et al., 1992; Geruschat, Fujiwara, & Emerson, 2012; Guth, Ashmead, Long, Wall, & Ponchillia, 2005). Somewhat unsurprisingly, impaired visual perception has negative safety implications in the context of traffic gap selection. Low-vision pedestrians, especially those with central (as opposed to peripheral) vision loss, exhibited delayed crossing decisions and smaller safety margins (i.e., less leeway before the oncoming vehicle's arrival) in a simulated traffic environment. Blind pedestrians are able to select safe gaps at a similar level of performance to sighted pedestrians in single-lane contexts, but perform significantly worse in more acoustically complex (e.g., two-lane) contexts. Visually impaired pedestrians are also disadvantaged by an inability to communicate nonverbally (i.e., visually) with drivers.

## Intrapersonal & Environmental Visual Impairment

A substantial amount of evidence that visual impairment presents a safety risk for pedestrians clearly exists. Visual impairment can take several forms and arise from a myriad of sources. Distraction via a secondary task, such as texting, can divert a pedestrian's visual attention away from the road environment (especially for cognitively complex secondary tasks). Sensory impairment, such as congenital blindness or immature development of retinal and/or cortical areas, can impede the process of hazard detection. Forms of visual impairment such as distraction and blindness, while of high relevance to pedestrian safety and worthy of empirical investigation, do not represent the entire breadth of factors which may impact a pedestrian's vision (and by extension their safety in the road environment). More acute and/or temporary forms of visual impairment can occur from intrapersonal and environmental sources. Alcohol intoxication and the presence of fog are common examples of intrapersonal and environmental impairment respectively.

## Alcohol

Psychoactive substances such as alcohol can affect perceptual, cognitive, and motor processes. On one hand alcohol can produce perceivably positive effects such as pleasurable emotions, decreased anxiety, and lowered inhibitions (Capito, Lautenbacher, & Horn-Hofmann, 2017). The perceived benefits of alcohol, however, also come with drawbacks including temporary perceptual and cognitive impairments, which can in turn lead to injury. Alcohol's perceptual, cognitive, and motor effects and role in the development of diseases such as liver cirrhosis and dementia render alcohol a significant causal factor in about 88,000 deaths in the United States annually (Stahre et al., 2014).

Alcohol specifically has been noted to inhibit vision (especially eye movements and visual tracking), auditory discrimination thresholds, motor skills, and cognitive functions such as memory, vigilance, dual-tasking performance, and reaction time (Chiles & Jennings, 1970; Moskowitz & Fiorentino, 2000; Pearson, Dawe, & Timney, 1999; Silva et al., 2017; Upile et al., 2007). Additionally, a growing body of research has shed light on how acute alcohol intoxication affects aspects of executive functioning including impaired decision making, poor planning, and perseveration of errors on cognitively complex tasks (Davis-Stober, McCarty, & McCarthy, 2019; Finn et al., 1999; George, Rogers, & Duka, 2005; Lyvers & Maltzman, 1991; Weissenborn & Duka, 2003). Specifically, intoxicated individuals appear to allocate attention preferentially to cues conducive to continued consumption, as well as exhibit increased impulsivity and a diminished ability to monitor their behavior and self-regulate their responses when presented with increased risk of unfavorable outcomes. Pre-consumption executive functioning, specifically a high working memory capacity, has been suggested to modulate the disinhibitory effects of alcohol.

Alcohol is an example of an intrapersonal source of perceptual impairment – alcohol's effects are observed within an individual, not the traffic environment. Neurologically, when consumed, alcohol acts as an agonist for the major inhibitory neurotransmitter gamma-aminobutyric acid (Kumar, Porcu, & Werner, 2009). Many of the harmful effects of alcohol arise from its metabolization, which involves two key enzymes: alcohol dehydrogenase and aldehyde dehydrogenase. Alcohol dehydrogenase first converts alcohol into acetaldehyde, a compound widely considered to be a carcinogen (Edenberg, 2007). Acetaldehyde is subsequently converted into acetate, which can then be converted into carbon dioxide and water for excretion from the body. The speed and efficiency of this process can vary from person to person due to reasons including levels of the two enzymes, genetics, nutrition, medications, and how much alcohol is consumed (NIH, 1997). Therefore the etiological perspective commonly employed in pedestrian safety research will prove useful in investigations regarding the impact of alcohol intoxication on pedestrian safety.

In the pedestrian context, alcohol intoxication has been cited in police accident reports as a major factor which may lead to collisions with vehicles (Ulfarsson, Kim, & Booth, 2010). Unfortunately, despite an estimated 36% of fatal pedestrian-vehicle collisions involving an intoxicated pedestrian (NHTSA, 2017), the pedestrian safety literature contains relatively few studies examining the impact of alcohol on pedestrian behavior or performance. The studies that do exist use observational or injury data analysis methodologies (e.g., Dultz et al., 2011; Holubowycz, 1995). To my knowledge, no controlled laboratory studies examining the effects of alcohol on components of the pedestrian task exist. More research, especially in the form of controlled laboratory studies, is needed to better understand how alcohol impacts pedestrian safety.

While to my knowledge no controlled studies exist regarding how alcohol affects pedestrians, the same is not true for another major group of roadway users: drivers. In addition to legislation and public awareness campaigns such as Mothers Against Drunk Driving, a substantial amount of research has been dedicated to understanding the effects of alcohol intoxication on vehicle drivers (see Irwin, Iudakhina, Desbrow, & McCartney, 2017, for a review). The attention is not unwarranted; intoxicated driving is responsible for thousands of deaths annually and over $30 billion in costs (Bouchery et al., 2011). Alcohol impairs drivers' cognition, motor functions, and inhibitory control, leading to riskier decisions and diminished ability to maintain speed and lane position (Weafer & Fillmore, 2012). Moreover, these effects are present even below the common legal limit of .08 g/dL BAC (Field et al., 2010). Overall, the scientific literature regarding the effects of alcohol on drivers presents a useful framework for future work in the domain of pedestrian safety.

## Environmental Occlusion

Alcohol intoxication is an example of how pedestrian visual perception may be impaired intrapersonally, but visual impairment can also arise from environmental factors. For example, many pedestrian injuries occur in locations where visibility is physically obstructed such as bends in the roadway, crests of hills, and streets with large numbers of parked cars (Ampofo-Boateng & Thompson, 1989; Roberts et al., 1995; LaScala, Gerber, & Gruenewald, 2000). In fact, an estimated 40-70% of young children's and 20% of young teenagers' accidents when crossing the street involve visual occlusion by a parked vehicle (van der Molen, 1981).

Conditions of visual occlusion, such as via parked vehicles or a tree with foliage extending into the pedestrian's line of sight, may be a factor through which differences in performance between experienced and inexperienced pedestrians surface. Studies in domains such as the sports sciences have found experienced athletes to perform better than inexperienced athletes on tasks involving tracking moving objects when vision is impaired by occlusion (Moreno, Luis, Salgado, Garcia, & Reina, 2005). In a pedestrian context, then, individuals less experienced in crossing streets with large numbers of parked vehicles – or inexperienced as pedestrians in general – may make more judgment errors about approaching traffic when their view is blocked by parked cars. Some empirical evidence even suggests the presence of parked vehicles (particularly illegally parked vehicles) can increase the likelihood of a pedestrian selecting a given traffic gap, possibly due to the parked vehicles making the crossing distance seem shorter and therefore safer (Yannis, Papadimitriou, & Theofilatos, 2010). Additionally, the tendency for people to preferentially attend to the visual modality even in disadvantageous situations (Colavita, 1974) could lead to failure to detect the sound of oncoming traffic when the pedestrian's view is occluded.

Adverse weather can also impair the ability of a person to see clearly, raising the likelihood of injury in contexts such as a crosswalk. For example, in Taiwan during the time period of 2011-2016, almost 33% of the 14,382 pedestrian-vehicle collisions resulting in injuries occurred under poor weather conditions – specifically rain or fog (Pai, Chen, Ma, Wu, Linkov, & Ma, 2019). Similar trends have been observed in the west as well, with 15.5% of fatal pedestrian-vehicle collisions in Washington State during the years 1981-1983 taking place during rain, snow, or fog (Mueller, Rivara, & Bergman, 1987).

The notion of fog negatively impacting pedestrian safety is relatively in line with what one might expect from a common-sense perspective. Fog reduces visual contrast of the road environment – that is, the perceivable difference in luminance between the brightest and darkest elements of the scene. Basic empirical research has found contrast to likely be a primary factor (alongside stimulus duration) in determining visuospatial memory performance, processed even before the stimulus's identity and meaning (Harley, Dillon, & Loftus, 2004). Visuospatial working memory is important for pedestrian visual search (Kovesdi & Barton, 2013) and therefore may be a mechanism through which fog might impact pedestrian safety.

While injury data suggest adverse weather conditions such as fog are hazardous for pedestrians, the state of the literature is analogous to that of the literature on alcohol's impact on pedestrian safety. Specifically, little to no research has examined the impact of conditions such as fog from the pedestrian's perspective – most scientific attention has been directed toward how fog affects drivers (e.g., Kang, Ni, & Andersen, 2008; Mueller & Trick, 2012;

Quétard et al., 2015; Trick, Lochner, Toxopeus, & Wilson, 2017). Fog reduces contrast of the road environment, and as a result drivers experience more difficult with tasks such as responding to traffic speed variations, impaired detection of target stimuli, and delayed hazard response times. Interestingly, results also seem to interact with factors such as participant age, experience level, and cognitive task load. A need exists for controlled laboratory studies to examine the effects of environmental sources of visual perceptual impairment, such as fog, on pedestrian safety. Understanding such factors from the perspective of all roadway users – drivers and pedestrians alike – is a vital step toward further reducing injury rates.

## Aims & Hypotheses

My dissertation addresses a gap in the pedestrian safety literature by systematically examining the effects of intrapersonal and environmental sources of perceptual impairment – alcohol intoxication and visual occlusion respectively – on specific stages of the pedestrian task. Specifically, I examined how each source of impairment impacts a person's performance in making time-to-contact estimations and gap selections. Performance on constructs known to be related to pedestrian visual perception, such as visuospatial working memory capacity, were also examined to account for possible factors which may influence the impact of impairment. In other words, my aim was to examine how different sources of visual impairment affect the same two tasks necessary for safe pedestrian crossing: estimating the remaining time until the nearest vehicle reaches the crosswalk and choosing a crossing opportunity. To accomplish this goal, I designed and conducted two studies.

Study A examined how intrapersonal sources of perceptual impairment impact time-to-contact estimates and traffic gap selections. Such sources act primarily on the participant's person rather than being a property of the external environment. Participants were impaired either in terms of visual perception alone or in the context of an additional cognitive impairment (i.e., alcohol intoxication versus a pair of goggles simulating just the visual effects of intoxication). I hypothesized both forms of intrapersonal perceptual impairment would result in decreased accuracy of time-to-contact estimates as well as more unsafe gap selections relative to an unimpaired state. Specifically, I expected alcohol intoxication, acting as both a visual and cognitive impairment, would produce the greatest impact on both indices of pedestrian safety. Visual acuity, contrast sensitivity, and visuospatial working memory are known to be linked to performance on visual perception tasks; therefore, I expected higher scores on each of the three constructs to be associated with better performance on both pedestrian tasks.

Study B examined how environmental sources of perceptual impairment impact time-to-contact estimates and traffic gap selections. Such sources act primarily from within the external environment. Participants' visual perception was impaired via an environmental source on either an ambient or acute level. Specifically, with an "ambient" impairment such as fog, there is an inherent ambiguity to whether a stimulus is detectable due to visibility decreasing with distance on a continuous basis. With an "acute" impairment such as an occluding tree, on the other hand, visibility is abruptly cut off. I hypothesized both forms of environmental perceptual impairment would result in decreased accuracy of time-to-contact estimates as well as more unsafe gap selections relative to an unimpaired state. Specifically, I expected the acute occlusion presented by a tree would produce the greatest impact on both indices of pedestrian safety. As with Study A, I also expected high performance on secondary constructs including visual acuity, contrast sensitivity, and visuospatial working memory would be associated with better performance on both pedestrian tasks.

# Chapter 2: Study A – Intrapersonal Impairment

## Method

### Sample

Studies of performance in simulated driving have found large effect sizes associated with alcohol intoxication, such as a Cohen's *d* of 0.8 (Kenntner-Mabiala, Kaussner, Kaufmann, & Hoffmann, 2015). However, due to a lack of a precedent for controlled studies involving alcohol in the pedestrian safety literature, I used a slightly more conservative effect size estimate of 0.6, yielding a necessary sample size of 20 participants to achieve a statistical power of .90. A sample of 23 participants aged 21-31 years (*M* = 22.78, *SD* = 2.17, 10 females) were drawn from the undergraduate student population at the University of Idaho. Although no variation in performance by sex was expected, efforts were made to collect a sample with equal numbers of males and females. The protocol was approved by the Institutional Review Board prior to data collection. Due to the ongoing COVID-19 pandemic at the time of data collection, all experimental procedures were carried out with protocols in place (e.g., mandatory personal protective equipment) to facilitate hygiene and social distancing.

### Apparatus

**Virtual Environment.** The pedestrian task procedures took place inside a virtual reality simulator built using the Unity 3D engine. The simulator depicts a realistic daytime suburban midblock crosswalk environment featuring aesthetics such as trees, yards, fences, sidewalks, and curbs. The crosswalk spans a two-way road measuring 8 m from curb to curb. The participant stands surrounded by four 55-inch 4K (2160 x 3840 resolution) displays, providing a 240-degree field of view of the virtual crosswalk. Vehicles were visually represented by a 3D model of a red four-door sedan. Audio was provided through KRK Rokit 8 studio monitors (36Hz - 40kHz frequency response) and adjusted to peak at 75 dBA for vehicle sounds.

Vehicular sound stimuli were from the same set as those used in earlier research (e.g., Barton, Ulrich, & Lew, 2012; Davis & Barton, 2017; Pugliese, Barton, Davis, & Lopez, 2019). to which interested readers should refer for more details regarding methodology and apparatuses involved in the creation of sound stimuli. The stimuli used in this study comprised recordings of a 2008 Toyota Camry in a real pedestrian setting (at night on a smooth road devoid of snow, ice, or gravel) passing a tripod-mounted recorder’s location from the left at two speeds, 8.05 km/h (5 mi/h) and 40.23 km/h (25 mi/h). Previous work by Barton, Ulrich and Lew (2011) has shown that left and right-side directionality of sound does not significantly affect pedestrians' detection judgments; therefore, I did not use any sounds of vehicles approaching from the right.

**Input devices.** Two participant input devices were used throughout the experiment. First, a USB number pad was mounted in front of the participant on a wooden rail. When using the number pad, the participant was instructed to use the same hand consistently and to keep their hand resting above the number pad. Second, a joystick designed for 3D movement was substituted for the number pad during a certain portion of the experiment. The participant was instructed to consistently use the same hand for all procedures involving the joystick.

## Measures & Procedure

**Health screening.** In order to increase safety and exclude participants at risk for adverse effects of interacting with the simulator (especially participants who were asked to consume alcohol), participants were asked to complete a computerized general health screening form. The form asked participants whether they had enough to eat and drink prior to participation, whether they are prone to dizziness, and whether they have a medical condition (such as pregnancy or diabetes) or are taking any medications which may have side effects in conjunction with alcohol. Participants who reported inadequate food or water intake, being prone to dizziness, or any medical concerns would have been excluded from the study; none of the recruited participants provided problematic answers.

**Alcohol abuse screening.** Participants were asked to complete the Luebeck Alcohol Dependence and Abuse Screening Test (LAST; Rumpf, Hapke, Meyer, & John, 2002). The LAST consists of seven questions pertaining to the participant's alcohol-related habits (e.g., "Are you always able to stop drinking when you want to?"). One point is added for each answer indicating increased risk of alcohol dependence or abuse. Refer to Appendix A for a complete list of questions on the test as well as the scoring protocol. Participants who scored more than one point on the LAST would have been excluded from the study; none of the recruited participants provided answers warranting exclusion.

**Sound localization & frequency sensitivity.** Participants' ability to perceive sounds of various frequencies and discriminate acoustic directionality was measured via a method used in previous work (Davis and Barton, 2017; Pugliese, Barton, Davis, & Lopez, 2019). Specifically, participants were asked to stand in a designated position equidistant between each of the studio monitors. Onscreen instructions (accompanied by narration from the researcher) instructed participants to listen for sounds coming out of the left and right speakers and to indicate the directionality of the sounds they hear. Specifically, the participant used the USB keypad's 4, 5, and 6 keys to indicate a sound coming from the left (4), a sound coming from the right (6), or the absence of any sound (5). Each trial comprised a pure tone coming from the left or right (or not at all) at one of the following frequencies: 100 Hz; 250 Hz; 440 Hz; 1 kHz; 10 kHz. The presentation of pure tones was calibrated to peak at 65 db.

**Visual acuity.** Participants were asked to stand 20 ft (~6.1 m) away from a wall-mounted Snellen eye chart and read aloud each line in sequence from top to bottom. The number of the lowest line read without any errors was recorded.

**Contrast sensitivity.** Participants were asked to stand 10 ft away from a wall-mounted contrast sensitivity chart. The chart contains six lines of "tumbling E" symbols. Participants were asked to read one line at a time, indicating for each symbol the direction of the E's arms (for example, a symbol resembling a regular letter E has arms pointing right, while a symbol resembling the letter W has arms pointing up). The number of the last line read without any errors was recorded.

**Walking speed.** Each participant's walking speed was measured along a 5 m (16.40 ft) indoor path. Participants were told the path was the same distance as the width of a single-lane road. Participants were asked to walk in a straight line at a normal speed, as if they were casually crossing a single-lane road. Participants were asked to repeat this procedure two more times for a total of three walking speed measurements, the average of which was recorded.

**Visuospatial performance.** The participant's visuospatial working memory and motor tracking were measured via a battery of two tests, the Corsi Block Task (Corsi, 1972) and the Trail Making Test (Reitan, 1958). The two tests are described below.

***Corsi Block Task.*** Participants were asked to complete the Corsi Block Task, a commonly used measure of visuospatial working memory (e.g., Gupta, Agnihotri, Telles, &

Balkrishna, 2019; Purser et al., 2012; Robinson & Brewer, 2016). Physical implementations of the Corsi Block Task typically involve participants attempting to mimic a sequence of taps across nine pseudorandomly placed targets (usually blocks). The target sequences gradually increase in length in a forward span manner with no repeated targets within a sequence, up to a typical maximum of nine target taps.

I developed and used a custom computerized version of the Corsi Block Task. Prior computerized implementations of the task such as eCorsi substitute flashing blocks for taps during target sequence presentation, and mouse clicks for taps during the participant's replication of the specified target sequence. Such electronic versions suffer from the lack of motor priming and as a result do not accurately reflect performance on physical versions of the task (Claessen, van der Ham, & van Zandvoort, 2015). My implementation of the task features three-dimensional images of blocks and a smoothly moving pointer, thereby preserving the physical characteristics and motor priming associated with traditional physical versions of the task. A screenshot of my Corsi Block Task implementation can be seen in Figure 2.1.

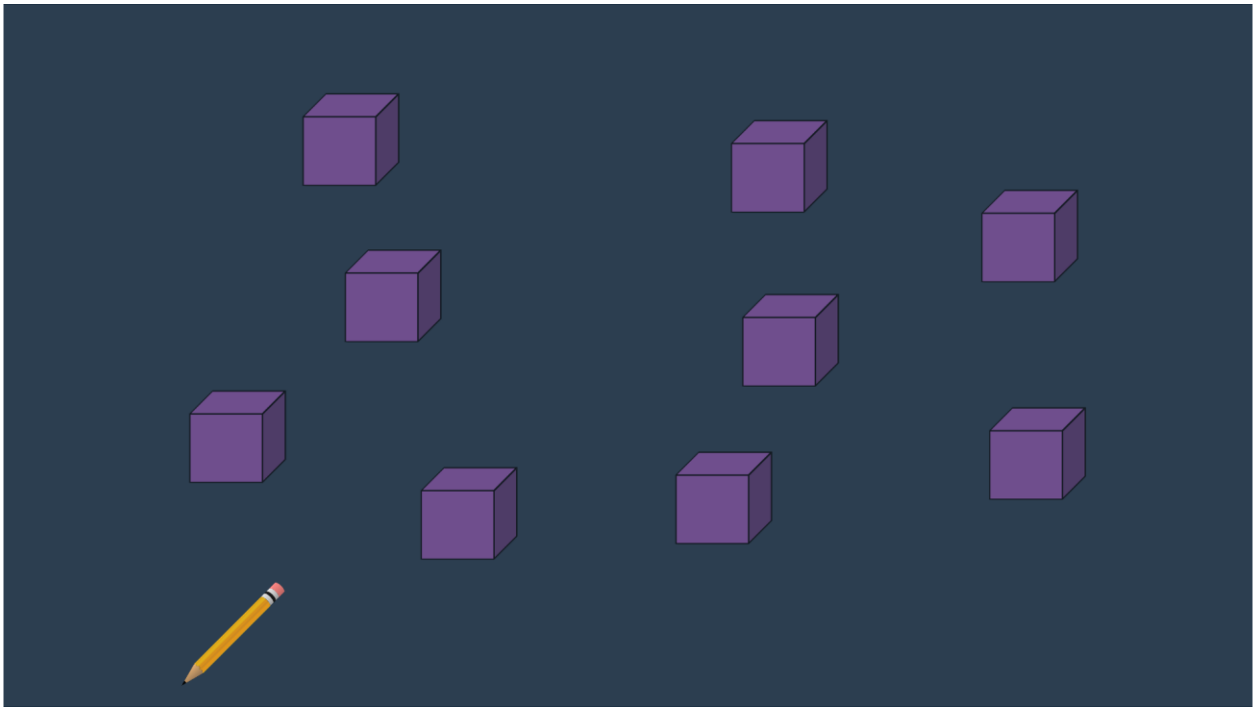
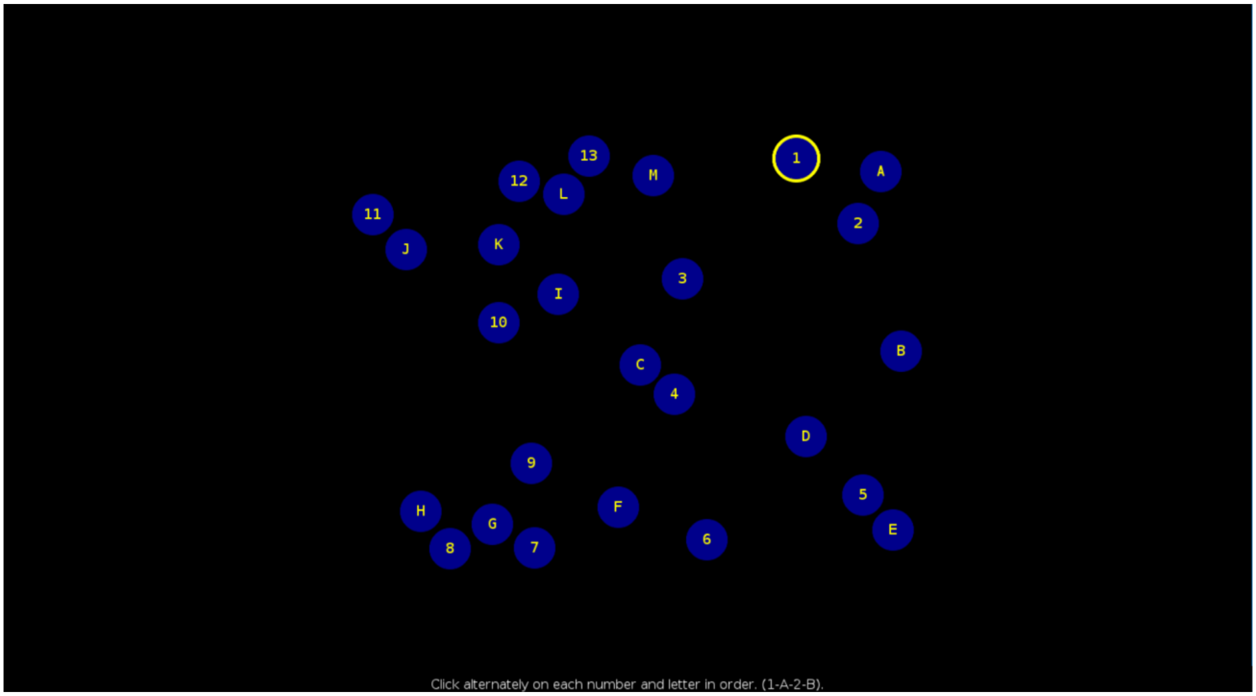


*Figure 2.1.* Custom electronic implementation of the Corsi Block Task. Unlike other electronic versions, my version features a moving pointer and three-dimensional block images.

Target block placements and target sequences were designed to match those used by Pagulayan, Busch, Medina, Bartok, and Krikorian (2006). Two sequences (i.e., trials) each of lengths 2, 3, 4, 5, 6, 7, 8, and 9 were presented in ascending order. The participant's *Corsi span*, the longest sequence successfully replicated for at least one trial, was multiplied by the number of correct trials to yield the dependent variable *total performance* (the maximum value for this variable was 16 trials * 9 span = 144).

***Trail Making Test.*** The Trail Making Test typically consists of about 25 circles distributed over a piece of paper (see Appendices B and C for example layouts of the forms). Participants completed three versions, or forms, on a computerized version of the task included with the Psychology Experiment Building Language library (Mueller & Piper, 2014). See Figure 2.2 for a screenshot of the program. Form A included circles numbered 1 to 25, form B included circles lettered A through Z, and form C's circles were alphanumerically labeled 1-13 and A-L. For form A the participant was asked to click the circles in ascending order beginning with 1. For form B the participant's task was be to click the circles in alphabetical order. For form C the participant had to click the circles in ascending order, but while alternating between numbers and letters (i.e., 1-A-2-B-3, etc). For all forms the participant was asked to complete the task as quickly and accurately as possible. Practice forms, each containing only four circles, were administered to familiarize the participant with the procedure.



Click alternately on each number and letter in order. (1-A-2-B).

*Figure 2.2.* The electronic implementation of the Trail-Making Test.

On each form, the participant’s number of erroneous clicks was recorded. An erroneous click was defined as a click in any region of the screen other than the next correct target circle in the ascending sequence. The ratio of erroneous clicks to targets was recorded as the dependent variable *trail-making accuracy*.

**Experimental manipulations.** Participants were randomly assigned to one of three experimental groups, hereafter referred to as "control," "goggles," and "alcohol." Participants randomly assigned to the control group were asked to continue participation normally, without the application of any additional sources of intrapersonal visual impairment. Participants randomly assigned to the goggles group were asked to wear a pair of Drunk Busters-brand alcohol impairment simulation goggles throughout the experimental procedures. The goggles featured clear lenses designed to simulate the visual distortion associated with alcohol intoxication at .04-.06 g/dL BAC, but without the additional cognitive impairments characteristic of actual intoxication. Participants assigned to the alcohol group were asked to consume alcohol according to a procedure which will now be discussed in detail.

***Alcohol.*** The alcohol group was asked to consume a cocktail of cranberry juice and vodka in the amount estimated to be necessary to reach a state of mild intoxication, specifically .05 g/dL blood alcohol concentration (BAC). The ratio of cranberry juice to vodka was 5:1 in order to increase the palatability of the beverage for quicker consumption. For example, a person requiring approximately 80 mL of vodka to reach the target BAC would receive a 480 mL cocktail. .05 g/dL was chosen as the target BAC for two reasons. First, .05 g/dL is a common threshold in the transportation safety literature (e.g., Irwin et al., 2017). Second, .05 g/dL is a level of intoxication associated with cognitive and visual impairments while still being below the legal limit in most American states. To estimate the amount of vodka (in g) necessary for a participant to reach the target .05 g/dL BAC, the following formula was used:

$g = (0.5 \times TBW) / 0.8$

Where 0.8 is the specific weight of alcohol, 0.5 is the target BAC in g/L, and TBW is the participant's total body water. Each participant's total body water was estimated by measuring the participant's height and weight then using the following formulas (Watson, Watson, & Batt, 1980):

Male TBW = 2.447 - (0.09156 x age) + (0.1074 x height in cm) + (0.3362 x weight in kg)

Female TBW = -2.097 + (0.1069 x height in cm) + (0.2466 x weight in kg)

All necessary calculations were carried out automatically via a specialized application which took the participant's age, sex, height, and weight as input then output the necessary amounts of vodka and fruit juice (in mL). A breath alcohol testing device was used to measure the participant's BAC 15 minutes after administration of alcohol. If necessary, the participant was asked to consume more alcohol or wait for their BAC to drop before continuation of the experimental procedure. This procedure for administration of alcohol was approved by the University of Idaho's Institutional Review Board and tested, without incident, with three participants in a pilot study.

**Pedestrian traffic tasks.** The main experiment took place in the virtual reality environment across three blocks of trials, each of which I will discuss in more detail below. During the first block the participant made time-to-contact estimations of approaching vehicles. The second block yielded thresholds for what gap sizes the participant deemed sufficient for crossing the virtual street. Finally, during the third block the participant actually moved their first-person avatar across the virtual street in streams of traffic partially derived from the gap size thresholds obtained during the second block. I will now discuss the procedure of each block in further detail.

***Block 1: Time-to-contact.*** The first block comprised a total of 12 trials, each trial consisting of a single vehicle approaching the virtual crosswalk from the left. At a certain point in the vehicle's approach, the vehicle disappeared and became inaudible. The participant was then asked to press the keypad's "enter" key to indicate when they believed the vehicle would have reached the crosswalk if the vehicle had not disappeared. This method of measuring time-to-contact, commonly known as a prediction motion task or coincidence anticipation task, has been previously used in multiple domains including pedestrian safety (Cavallo & Laurent, 1988; Pugliese, Barton, Davis, & Lopez, 2019; Tresilian, 1995).

Trials differed according to two factors. First, vehicles traveled at one of two speeds: 19.31 km/h (12 mi/h) or 40.23 km/h (25 mi/h). Second, the disappearance time of the vehicle – specifically, the vehicle's distance in seconds from the center of the crosswalk at the moment the vehicle becomes invisible and inaudible – was either 3 s, 5 s, or 7 s. Each of the six unique trials were presented twice for a total of 12 trials. The end of a trial was marked by the occurrence of either of two events: the participant making a time-to-contact estimation by pressing the appropriate key, or the participant failing to make a time-to-contact estimation before the vehicle would have traveled 5 s past the center of the crosswalk. The participant's time-to-contact estimate (if any) was recorded as the imperceptible vehicle's distance in seconds away from the center of the crosswalk at the moment the participant pressed the appropriate key. "Misses" (i.e., failures to make a time-to-contact estimation before the automatic end of the trial) were also recorded. Two practice trials, each comprising a vehicle traveling at 8.05 km/h (5 mi/h) with either a 2 s or 4 s disappearance time, were presented to familiarize the participant with the procedure.

***Block 2: Gap thresholds.*** The second block comprised two trials. Each trial contained 18 traffic gaps (i.e., 19 individual vehicles) of sizes ranging from 2 seconds to 6 seconds in 0.5-second increments, for a total of nine unique gap sizes. The gaps were presented twice each and in a randomized order for each trial. For example, a 2-second gap could be followed immediately by a 4.5-second gap, or vice versa. The two trials differed with respect to vehicle speed. The vehicles in trial 1 traveled at 19.31 km/h (12 mi/h) while the vehicles in trial 2 traveled at 40.23 km/h (25 mi/h). Vehicles always approached from the left (i.e., in the nearside lane).

During both trials of block 2 the participant was asked to press the number pad’s “enter” key to indicate traffic gaps they deemed sufficient for safe crossing. The gap sizes selected by the participant were automatically recorded by the simulator software and used to calculate several variables. Two of these variables were thresholds, or more specifically, the averages of the two smallest gap sizes selected for each trial. For example, if the two smallest gaps selected during trial 1 are 2 seconds and 3 seconds, the participant’s threshold for 12 mi/h traffic would be 2.5 seconds. If two gap sizes are tied for smallest (for example, if both 2-second gaps were chosen), then that gap size would be classified as the threshold. These thresholds were used to scale the traffic gaps in block 3, which I will now describe.

***Block 3: Gap selection.*** The third block consisted of 8 trials, each comprising a stream of traffic approaching from the left and varying according to two characteristics. First, the vehicles in the stream of traffic traveled either at high speed (40.23 km/h, or 25 mi/h) or at low speed (19.31 km/h, or 12 mi/h). Second, the gaps in the stream of traffic represented either a high risk of getting hit via traffic gaps too small to safely cross through, or a low risk of getting hit via gaps large enough to safely cross through with room to spare. Specifically, “too small” and “large enough” were defined via the thresholds calculated in block 2 for each vehicle speed. The threshold for a given speed was multiplied by either 1.5, 1.3, 0.7, or 0.5 to yield traffic gaps 50% larger, 30% larger, 30% smaller, or 50% smaller, respectively, than necessary to safely cross through. 50% and 30% smaller represented a high risk of getting hit, while 50% and 30% larger represented a low risk of getting hit. Each of the four unique combinations of traffic stream manipulations were presented two times each in a randomized order, for a total of 8 trials.

During each trial the participant was asked to use a joystick to move their first-person avatar across the street. Pushing forward on the joystick moved the avatar forward; backward movement was not possible. The avatar’s walking speed was set to match the participant's own walking speed (for which the measurement procedure was previously discussed).

The trial ended if any of the following conditions were met: if the avatar safely reached the other side of the street, if the avatar got hit by a vehicle, or if the final car in the stream of traffic reached the crosswalk before either of the other two conditions were met. The simulator software automatically recorded dichotomous variables indicating which of these conditions were met for each trial, as well as a variable indicating the size of the gap the participant chose to attempt to cross through (if applicable). A *safety gap* variable was recorded for each trial, defined as the nearest approaching vehicle's distance from the avatar's lateral position at the moment the avatar clears the traffic stream. This safety gap variable was normalized as the ratio of the vehicle's time-to-contact to the total size of the gap. For example, getting through a six-second gap with two seconds to spare would yield a safety gap of 2/6, or .33. In addition to safety gap, the simulator software also recorded the number of cars the participant allowed to pass before either successfully crossing or getting hit (i.e., a speed-independent measure of time spent at the curbside).

**Overall procedure.** Participation comprised the following steps. First, the informed consent process began. At this time participants were asked to provide legal identification as proof of age. Second, participants were asked to complete the health screening and alcohol abuse screening. Third, participants were randomly assigned to one of the experimental conditions (alcohol, goggles, or control). The breath alcohol testing device was used to establish a baseline BAC of zero for participants assigned to the alcohol group, followed by commencement of the alcohol administration procedure (including necessary wait times). Participants assigned to the goggles group were asked to wear them for the remainder of the study. Fourth, participants were asked to complete the visual acuity, contrast sensitivity, and sound localization tasks. Fifth, participants were asked to complete the visuospatial performance tasks. Sixth, participants' walking speed was measured. Finally, participants were asked to provide basic demographic information and complete the pedestrian traffic tasks in the virtual reality simulator, with three-minute breaks between blocks. At the conclusion of the study participants in the alcohol group were encouraged to remain in the lab until a breath alcohol reading of zero BAC could be obtained.

## Pilot Testing

Pilot testing was conducted with 3 participants, without incident, in order to identify any problems with the protocol or measures.

### Analyses

Analyses proceeded in several steps. First, descriptive statistics (such as age and sex) were examined across all dependent variables. Data normality was also assessed during this step. Second, a series of between-subjects ANOVAs assessed differences in perceptual variables (visual acuity, etc.) according to interpersonal perceptual impairment group. Third, a mixed ANOVA was used to test for main effects and interactions among time-to-contact estimates, intrapersonal perceptual impairment, and traffic characteristics. Fourth, another mixed ANOVA was conducted to test for main effects and interactions among safety gaps, traffic characteristics, and intrapersonal perceptual impairment. Fifth, a mixed ANOVA was conducted to test for main effects and interactions among cars allowed to pass before initiating an action, traffic characteristics, and intrapersonal perceptual impairment. Sixth, bivariate correlations were conducted to test for associations between perceptual variables (visual acuity, etc.) and pedestrian task performance variables (time-to-contact and safety gaps). Finally, risk ratios were calculated to assess the risk of getting hit by a virtual vehicle when under the influence of alcohol (alcohol group) or subject to the visual impairment associated with intoxication (goggles group).

## Results

### Descriptive Statistics and Data Quality

Sex and age differences were examined in time-to-contact errors, safety gaps, visual acuity, contrast sensitivity, and visuospatial performance. No statistically significant differences were found. Sex and age were excluded from all subsequent analyses. Descriptive statistics for time-to-contact errors and safety gaps are presented in tables 2.1 and 2.2 respectively, and graphically in figures 2.3 and 2.4. Descriptive statistics for visual acuity, contract sensitivity, and visuospatial performance variables are presented in table 2.3. Data normality was checked with a series of Q-Q plots. None of the measures exhibited any unusual distributional characteristics.

Table 2.1

*Means (SD in parentheses) for time-to-contact judgment error across impairment conditions at each level of speed and disappearance time.*

| | 3-second Disappearance | | 5-second Disappearance | | 7-second Disappearance | |
|---|---|---|---|---|---|---|
| | 12mph | 25mph | 12mph | 25mph | 12mph | 25mph |
| Alcohol | 1.07 (0.69) | 1.61 (0.97) | 1.53 (0.84) | 2.74 (1.88) | 1.96 (1.04) | 3.48 (2.13) |
| Goggles | 0.69 (0.26) | 0.74 (0.45) | 1.57 (0.55) | 1.5 (0.77) | 2.4 (1.19) | 1.78 (0.81) |
| Control | 0.58 (0.22) | 0.67 (0.54) | 0.76 (0.44) | 0.9 (0.71) | 1.5 (0.59) | 1.26 (0.86) |

*Note. N* = 23.

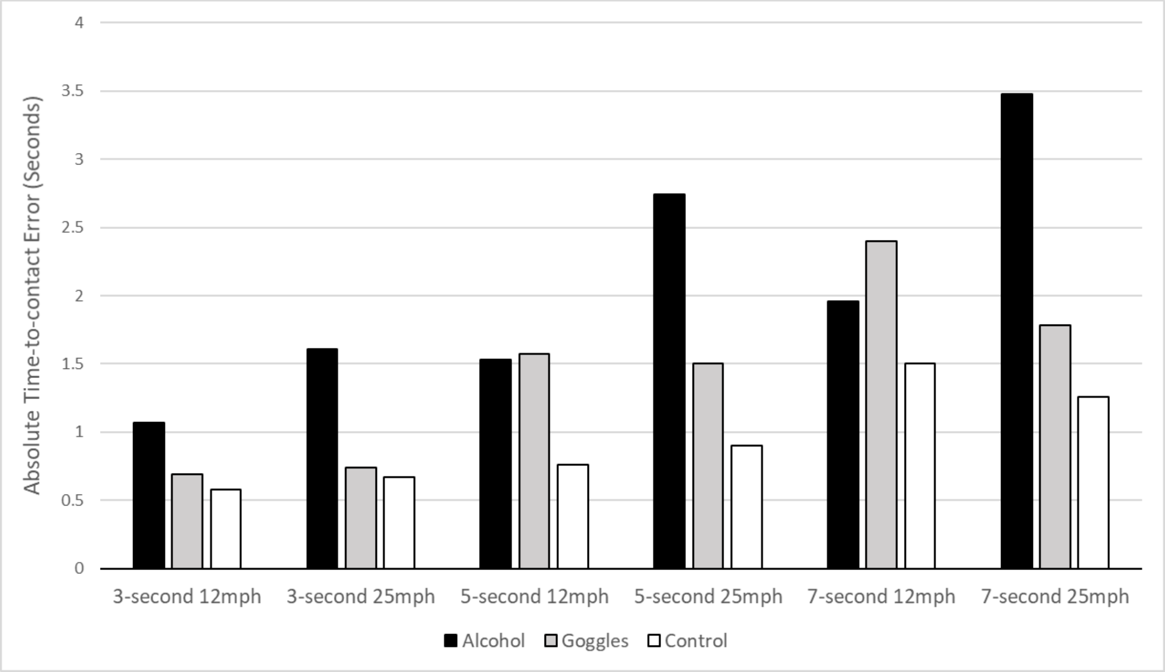


*Figure 2.3.* Mean time-to-contact judgment error across impairment conditions at each level of speed and disappearance time.

Table 2.2

*Means (SD in parentheses) for safety gap across impairment conditions at each level of speed and disappearance time.*

| | Small Gap | | Large Gap | |
|---|---|---|---|---|
| | 12mph | 25mph | 12mph | 25mph |
| Alcohol | 0.68 (0.42) | 0.53 (0.45) | 0.55 (0.05) | 0.50 (0.14) |
| Goggles | 0.72 (0.41) | 0.65 (0.38) | 0.57 (0.08) | 0.57 (0.09) |
| Control | 0.79 (0.31) | 0.72 (0.39) | 0.65 (0.07) | 0.61 (0.06) |

*Note*. *N* = 23.

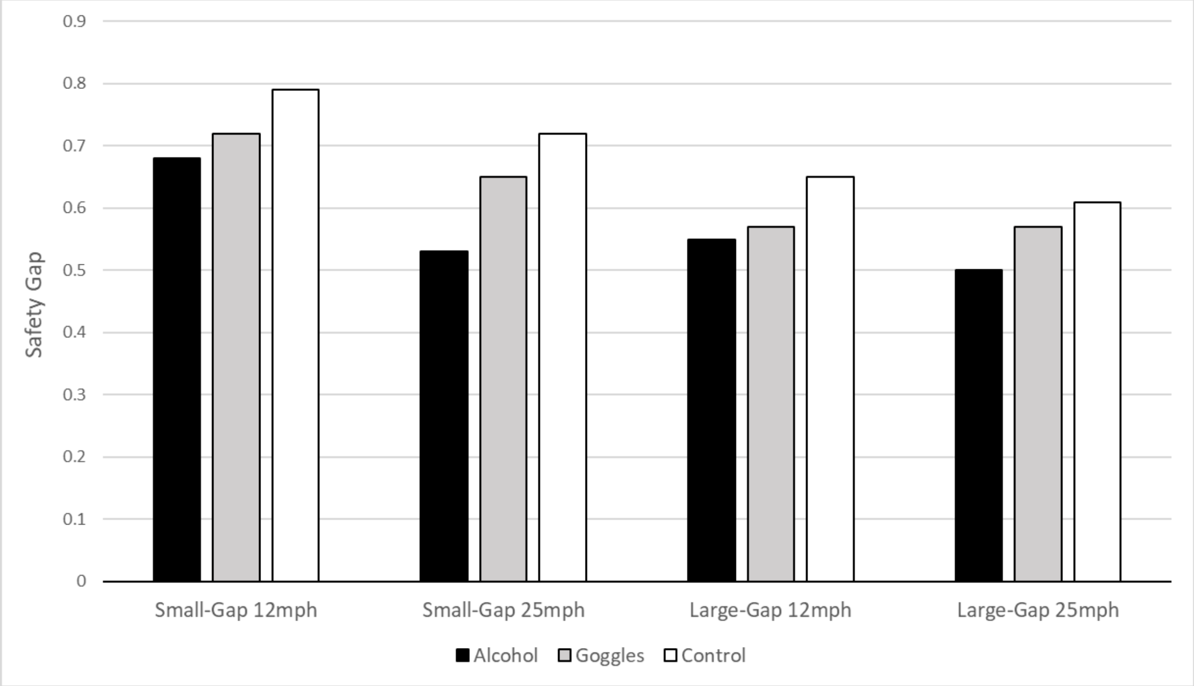


*Figure 2.4.* Mean safety gap across impairment conditions at each level of speed and disappearance time.

Table 2.3

*Means (SE in parentheses) for perceptual and visuospatial performance variables across impairment conditions.*

| | Visual Acuity (0 - 11) | Contrast Sensitivity (0 - 6) | Sound Localization (0 - 12) | Corsi Score (0 - 144) | Trail-Making Accuracy (0 - 1) |
|---|---|---|---|---|---|
| Alcohol | 7.14 (1.12) | 3.86 (0.63) | 10.57 (0.43) | 43.57 (6.13) | 0.86 (0.05) |
| Goggles | 5.75 (0.90) | 3.38 (0.60) | 11.00 (0.27) | 52.75 (7.69) | 0.86 (0.03) |
| Control | 8.75 (0.75) | 5.00 (0.54) | 11.50 (0.27) | 55.25 (5.44) | 0.92 (0.02) |

*Note*. $N = 23$.

## Perceptual Variables

Between-subjects ANOVAs were conducted to assess differences in visual acuity, contrast sensitivity, sound localization, and visuospatial performance between intrapersonal perceptual impairment groups. No significant differences were found.

Pearson bivariate correlations were conducted to examine the relationships between perceptual variables and pedestrian task performance variables (time-to-contact and safety gaps). No significant correlations emerged.

## Time-to-contact

A mixed impairment (3) × disappearance time (3) × speed (2) ANOVA was conducted to test for differences between the alcohol, goggles, and control groups in time-to-contact errors. A significant main effect of impairment condition was found, $F(2, 20) = 10.34$, $p < .01$, partial $\eta^2 = .51$. Bonferroni follow-up tests indicated time-to-contact judgment errors were significantly greater in the alcohol condition ($M = 2.064$, $SE = .18$) than in the control condition ($M = .95$, $SE = .17$). Time-to-contact judgment errors in the goggles condition ($M =$

1.44, *SE* = .17) fell between the alcohol and control conditions but were not significantly different from either.

A significant main effect of disappearance time was found, $F(2, 40) = 30.21$, $p < .01$, partial $\eta^2 = .60$. Pairwise comparisons revealed time-to-contact judgment errors were significantly different between the three disappearance time conditions. Specifically, time-to-contact judgment errors in the 3-second disappearance condition ($M = .89$, $SE = .09$) were significantly smaller than in the 5-second disappearance condition ($M = 1.50$, $SE = .14$), which in turn were significantly smaller than in the 7-second disappearance condition ($M = 2.06$, $SE = .15$).

## Gap Selection

A mixed impairment (3) × disappearance time (3) × speed (2) ANOVA was conducted to test for differences between the alcohol, goggles, and control groups in safety gaps. No significant main effects or interactions were found.

Risk ratio calculations were conducted to examine the strength of association between intrapersonal visual impairment and collision with a vehicle. Frequencies for participants with and without virtual vehicle collisions according to visual impairment condition are presented in table 2.4 (note that the alcohol and goggles conditions were combined as a single level of impairment). The cumulative incidence of vehicular collision for participants experiencing visual impairment was .33; the cumulative incidence for participants in the control condition was .125. In other words, participants who experienced visual impairment had 2.64 times the risk of getting hit by a virtual vehicle compared to participants who did not have to contend with either form of intrapersonal visual impairment.

Table 2.4

*Frequencies and cumulative incidence of vehicular collision for impaired and non-impaired participants.*

| Impairment | Hit | Not hit | Total | Incidence |
|---|---|---|---|---|
| Yes | 5 | 10 | 15 | .33 |
| No | 1 | 7 | 8 | .125 |

*Note*. $N = 23$.

The number of vehicles allowed to pass before enacting an action (successfully crossing or getting hit) was examined in an impairment (3) × gap size (2) × speed (2) mixed ANOVA testing for differences between environmental visual impairment conditions. A significant main effect of gap size was found, $F(1, 20) = 972.52$, $p < .01$, partial $\eta^2 = .98$. Pairwise comparisons revealed that the mean was greater for the small gaps condition ($M = 6.28$; $SE = .16$) than the large gaps condition ($M = 1.41$, $SE = .08$). Descriptive data are presented in Figure 2.5.

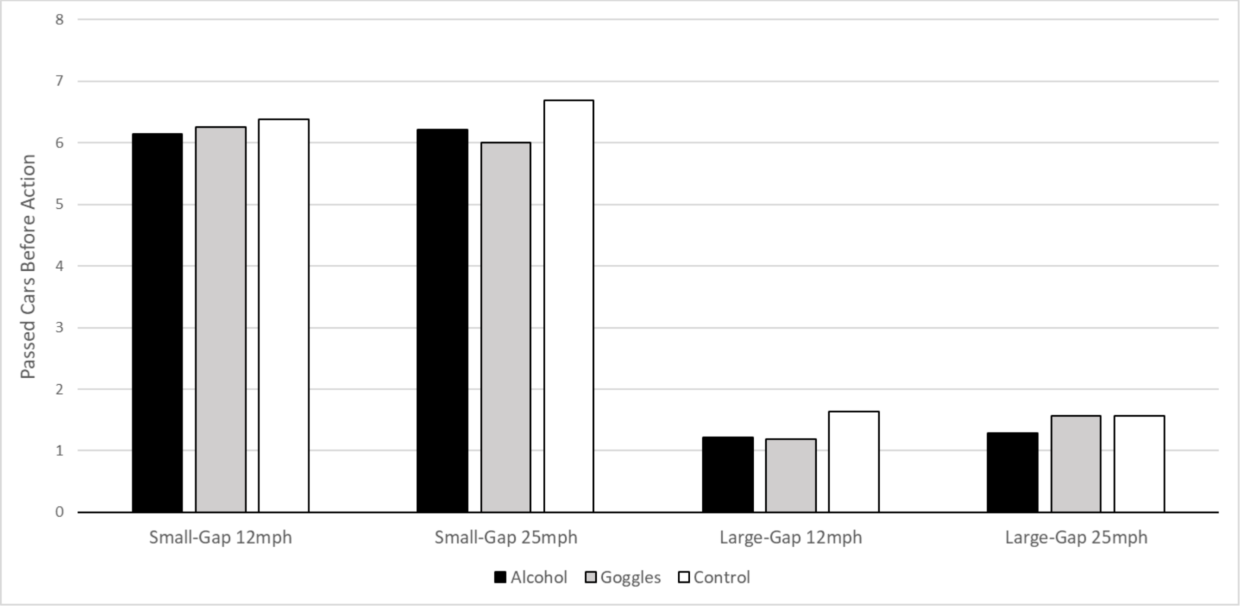


*Figure 2.5.* Mean number of vehicles allowed to pass before enacting an action across impairment conditions at each level of speed and gap size.

# Chapter 3: Study B – Environmental Impairment

## Method

### Sample

I conducted a power analysis to calculate the sample size required for study B. Studies of performance in simulated driving have found only small to moderate effect sizes associated with occlusion via fog (e.g., Trick et al., 2017). Therefore, I used a conservative effect size estimate of 0.3, yielding a necessary sample size of 50 participants to achieve a statistical power of .90. A sample of 52 participants aged 18-34 years (*M* = 20.26, *SD* = 3.06, 27 females) were drawn from the undergraduate student population at the University of Idaho. Although no variation in performance by sex was expected, efforts were made to collect a sample with equal numbers of males and females. The protocol was approved by the Institutional Review Board prior to data collection. Due to the ongoing COVID-19 pandemic at the time of data collection, all experimental procedures were carried out with protocols in place (e.g., mandatory personal protective equipment) to facilitate hygiene and social distancing.

### Apparatus

**Virtual Environment.** The pedestrian task procedures took place inside a virtual reality simulator built using the Unity 3D engine. The simulator depicted a realistic daytime suburban midblock crosswalk environment featuring aesthetics such as trees, yards, fences, sidewalks, and curbs. The crosswalk spanned a two-way road measuring 8 m from curb to curb. The participant stood surrounded by four 55-inch 4K (2160 x 3840 resolution) displays, providing a 240-degree field of view of the virtual crosswalk. Vehicles were visually represented by a 3D model of a red four-door sedan. Audio was provided through KRK Rokit 8 studio monitors (36Hz - 40kHz frequency response) and adjusted to peak at 75 dBA for vehicle sounds.

Vehicular sound stimuli were from the same set as those used in earlier research (e.g., Barton, Ulrich, & Lew, 2012; Davis & Barton, 2017; Pugliese, Barton, Davis, & Lopez, 2019). to which interested readers should refer for more details regarding methodology and apparatuses involved in the creation of sound stimuli. The stimuli used in this study comprised recordings of a 2008 Toyota Camry in a real pedestrian setting (at night on a smooth road devoid of snow, ice, or gravel) passing a tripod-mounted recorder's location from the left at two speeds, 8.05 km/h (5 mi/h) and 40.23 km/h (25 mi/h). Previous work by Barton, Ulrich and Lew (2011) has shown that left and right-side directionality of sound does not significantly affect pedestrians' detection judgments; therefore, I did not use any sounds of vehicles approaching from the right.

**Input devices.** Two participant input devices were used throughout the experiment. First, a USB number pad was mounted in front of the participant on a wooden rail. When using the number pad, the participant was instructed to use the same hand consistently and to keep their hand resting above the number pad. Second, a joystick designed for 3D movement was substituted for the number pad during a certain portion of the experiment. The participant was instructed to consistently use the same hand for all procedures involving the joystick.

## Measures & Procedure

**Health screening, walking speed, & audiovisual tasks.** The health screening, sound localization test, visual acuity test, contrast sensitivity test, visuospatial performance tests, and walking speed measurement procedure from Study A were used, with two differences. First, the health screening did not ask questions pertaining to alcohol-related risks due to the lack of alcohol administration in study B. Second, participants were not asked to complete the Luebeck Alcohol Dependence and Abuse Screening Test, again due to study B not requiring the administration of alcohol to participants.

**Pedestrian traffic tasks.** The main experiment took place in the virtual reality environment across three blocks of trials, each of which I will discuss in more detail below. During the first block the participant made time-to-contact estimations of approaching vehicles. The second block yielded thresholds for what gap sizes the participant deemed sufficient for crossing the virtual street. Finally, during the third block the participant actually moved their first-person avatar across the virtual street in streams of traffic partially derived from the gap size thresholds obtained during the second block. Two of the blocks shared a set of independent variables corresponding to the presence or absence of two sources of environmental perceptual impairment (specifically fog and the presence of an occluding tree). I will now describe the implementation of the fog and occluding tree, followed by a discussion of the procedures for each block.

***Environmental manipulations.*** Blocks 1 and 3 featured two forms of environmental manipulations producing unique forms of perceptual impairment. First, the presence of fog was accomplished via a post-processing effect included with the Unity software powering the virtual reality simulator. When present, the fog was set at such a density that visibility was limited to 100 m. This represents the threshold where visibility is typically considered to be zero and precautions such as road closures are enacted. Additionally, Mueller and Trick (2012) found a relatively weak effect on driving safety with fog visibility set to 600 m, so a stronger manipulation (i.e., 100 m visibility) may produce larger differences in the pedestrian context. The second form of environmental perceptual impairment, the presence of an occluding tree, produced a more acute form of visibility cutoff. When present, the tree was positioned such that the foliage extended into the participant’s line of sight down the road, limiting visibility to 100 m, the same threshold as for the fog manipulation. Such parity allowed for better comparison between the two manipulations – that is, any differences that arise are due to the acute/ambient nature of the impairment source itself, and not confounded by factors such as different visibility cutoffs.

***Block 1: Time-to-contact.*** The first block comprised a total of 32 trials, each trial consisting of a single vehicle approaching the virtual crosswalk from the left. At a certain point in the vehicle's approach, the vehicle disappeared and became inaudible. The participant was then asked to press the keypad's "enter" key to indicate when they believed the vehicle would have reached the crosswalk if the vehicle had not disappeared. This method of measuring time-to-contact, commonly known as a prediction motion task or coincidence anticipation task, has been previously used in multiple domains including pedestrian safety (Cavallo & Laurent, 1988; Pugliese, Barton, Davis, & Lopez, 2019; Tresilian, 1995).

Trials varied according to four factors. First, vehicles traveled at one of two speeds: 19.31 km/h (12 mi/h) or 40.23 km/h (25 mi/h). Second, the disappearance time of the vehicle – specifically, the vehicle's distance in seconds from the center of the crosswalk at the moment the vehicle becomes invisible and inaudible – was either 3 s or 7 s. Third and fourth, fog and an occluding tree were each either present or absent. Each of the sixteen unique trials were presented twice for a total of 32 trials. The end of a trial was marked by the occurrence of either of two events: the participant made a time-to-contact estimation by pressing the appropriate key, or the participant failed to make a time-to-contact estimation before the vehicle would have traveled 5 s past the center of the crosswalk. The participant's time-to-contact estimate (if any) was recorded as the imperceptible vehicle's distance in seconds away from the center of the crosswalk at the moment the participant pressed the appropriate key. "Misses" (i.e., failures to make a time-to-contact estimation before the automatic end of the trial) were also recorded. Two practice trials, each comprising a vehicle traveling at 8.05 km/h (5 mi/h) with either a 2 s or 4 s disappearance time but without fog or an occluding tree, were presented to familiarize the participant with the procedure. Lastly, the participant was allowed a two-minute break at the midway point (i.e., after the 16th trial).

***Block 2: Gap thresholds.*** The second block comprised two trials. Each trial contained 18 traffic gaps (i.e., 19 individual vehicles) of sizes ranging from 2 seconds to 6 seconds in 0.5-second increments, for a total of nine unique gap sizes. The gaps were presented twice each and in a randomized order for each trial. For example, a 2-second gap could be followed immediately by a 4.5-second gap, or vice versa. The two trials differed with respect to vehicle speed. The vehicles in trial 1 traveled at 19.31 km/h (12 mi/h) while the vehicles in trial 2 traveled at 40.23 km/h (25 mi/h). Vehicles always approached from the left (i.e., in the nearside lane). Neither fog nor occluding tree were present for either trial.

During both trials of block 2 the participant was asked to press the number pad’s “enter” key to indicate traffic gaps they deem sufficient for safe crossing. The gap sizes selected by the participant were automatically recorded by the simulator software and used to calculate several variables. Two of these variables were thresholds, or more specifically, the averages of the two smallest gap sizes selected for each trial. For example, if the two smallest gaps selected during trial 1 are 2 seconds and 3 seconds, the participant’s threshold for 12 mi/h traffic was 2.5 seconds. If two gap sizes were tied for smallest (for example, if both 2-

second gaps were chosen), then that gap size was classified as the threshold. These thresholds were used to scale the traffic gaps in block 3, which I will now describe.

***Block 3: Gap selection.*** The third block consisted of 32 trials, each comprising a stream of traffic approaching from the left and varying according to four characteristics. First, the vehicles in the stream of traffic traveled either at high speed (40.23 km/h, or 25 mi/h) or at low speed (19.31 km/h, or 12 mi/h). Second, the gaps in the stream of traffic represented either a high risk of getting hit via traffic gaps too small to safely cross through, or a low risk of getting hit via gaps large enough to safely cross through with room to spare. Specifically, "too small" and "large enough" were defined via the thresholds calculated in block 2 for each vehicle speed. The threshold for a given speed was multiplied by either 1.5, 1.3, 0.7, or 0.5 to yield traffic gaps 50% larger, 30% larger, 30% smaller, or 50% smaller, respectively, than necessary to safely cross through. 50% and 30% smaller represented a high risk of getting hit, while 50% and 30% larger represented a low risk of getting hit. To reduce trial-to-trial familiarity, each gap size was further multiplied by a random number between .95 and 1.05, producing a limited normal curve of gap sizes centered around the initial multiplier. Third and fourth, fog and an occluding tree will each be either present or absent. Each of the sixteen unique combinations of manipulations were presented two times each in a randomized order, for a total of 32 trials. Participants were allowed a two-minute break at the midway point (i.e., after the 16th trial).

During each trial the participant was asked to use a joystick to move their first-person avatar across the street. Pushing forward on the joystick moved the avatar forward; backward movement was not possible. The avatar's walking speed was set to match the participant's own walking speed (for which the measurement procedure was previously discussed).

The trial ended if any of the following conditions are met: if the avatar safely reached the other side of the street, if the avatar got hit by a vehicle, or if the final car in the stream of traffic reached the crosswalk before either of the other two conditions were met. The simulator software automatically recorded dichotomous variables indicating which of these conditions were met for each trial, as well as a variable indicating the size of the gap the participant chose to attempt to cross through (if applicable). A *safety gap* variable was recorded, defined as the nearest approaching vehicle's distance from the avatar's lateral position at the moment the avatar cleared the traffic stream. This safety gap variable was normalized as the ratio of the vehicle's time-to-contact to the total size of the gap. For example, getting through a six-second gap with two seconds to spare would yield a safety gap of 2/6, or .33. In addition to safety gap, the simulator software also recorded the number of cars the participant allowed to pass before either successfully crossing or getting hit (i.e., a speed-independent measure of time spent at the curbside).

**Overall procedure.** Participation comprised the following steps. First, the informed consent process began. Second, participants were asked to complete the health screening. Third, participants were asked to complete the visual acuity, contrast sensitivity, and sound localization tasks. Fourth, participants were asked to complete the visuospatial performance tasks. Fifth, participants' walking speed was measured. Finally, participants were asked to provide basic demographic information and complete the pedestrian traffic tasks in the virtual reality simulator, with three-minute breaks between blocks.

### Pilot Testing

Pilot testing was conducted with 3 participants, without incident, in order to identify any problems with the protocol or measures. Several procedures had been previously tested or used in previous studies.

### Analyses

Analyses proceeded in several steps. First, descriptive statistics (such as age and sex) were examined across all dependent variables. Data normality was also assessed during this step. Second, a repeated-measures ANOVA was used to test for main effects and interactions among time-to-contact estimates, environmental perceptual impairment, and traffic characteristics. Third, another repeated-measures ANOVA was conducted to test for main effects and interactions among safety gaps, and environmental perceptual impairment. Fourth, bivariate correlations were conducted to test for associations between perceptual variables (visual acuity, etc.) and pedestrian task performance variables (time-to-contact and safety gaps). Finally, a repeated-measures ANOVA was conducted to test for main effects and interactions among cars allowed to pass before initiating an action and environmental perceptual impairment. Post-hoc paired t-tests with Bonferroni corrections were used to further analyze any interactions.

## Results

### Descriptive Statistics and Data Quality

Sex and age differences were examined in time-to-contact errors, safety gaps, visual acuity, contrast sensitivity, and visuospatial performance. No statistically significant differences were found. Sex and age were excluded from all subsequent analyses. Descriptive statistics for time-to-contact errors and safety gaps are presented in tables 3.1 and 3.2 respectively, and graphically in figures 3.1 and 3.2. Descriptive statistics for visual acuity, contract sensitivity, and visuospatial performance variables are presented in table 3.3. Data normality was checked with a series of Q-Q plots. None of the measures exhibited any unusual distributional characteristics. Five participants' data had to be discarded due to failure to follow experimental protocol (for example, never pressing the button to estimate a vehicle's time to arrival, or intentionally getting hit during crossing trials). Analyses proceeded with data for the remaining 47 participants.

Table 3.1

*Means (SD in parentheses) for time-to-contact judgment error across impairment conditions at each level of speed and disappearance time.*

| | 3-second Disappearance | | | 7-second Disappearance | | |
|---|---|---|---|---|---|---|
| | | Fog | No Fog | | Fog | No Fog |
| Speed: 12 mi/h | Occlusion | .89 (.53) | .86 (.47) | Occlusion | 2.06 (1.15) | 2.01 (1.24) |
| | No Occlusion | .92 (.55) | .84 (.50) | No Occlusion | 1.95 (1.18) | 1.94 (1.13) |
| | | Fog | No Fog | | Fog | No Fog |
| Speed: 25 mi/h | Occlusion | 1.02 (.62) | .89 (.55) | Occlusion | 2.06 (1.18) | 2.02 (1.37) |
| | No Occlusion | .83 (.51) | .98 (.56) | No Occlusion | 2.07 (1.27) | 1.81 (1.06) |

*Note. N* = 47.

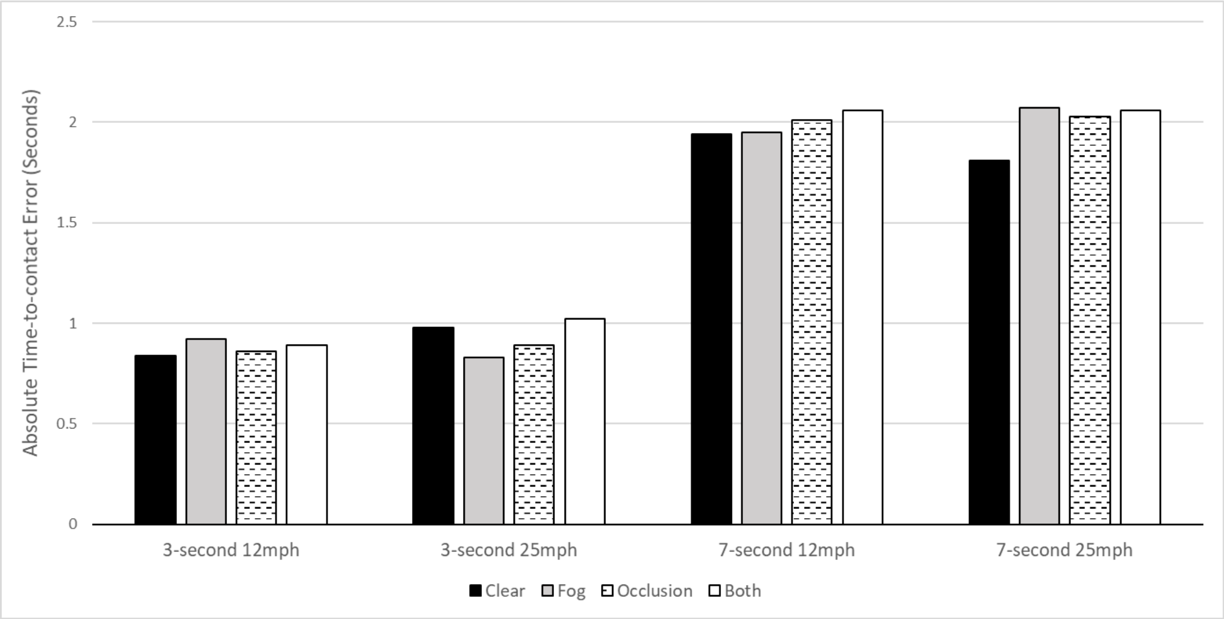


*Figure 3.1.* Mean time-to-contact judgment error across impairment conditions at each level of speed and disappearance time.

Table 3.2

*Means (SD in parentheses) for safety gap across impairment conditions at each level of speed and disappearance time.*

| | Small Gaps | | | Large Gaps | | |
|---|---|---|---|---|---|---|
| | | Fog | No Fog | | Fog | No Fog |
| Speed: 12 mi/h | Occlusion | .89 (.23) | .81 (.34) | Occlusion | .58 (.11) | .59 (.09) |
| | No Occlusion | .76 (.38) | .86 (.27) | No Occlusion | .56 (.06) | .59 (.09) |
| | | Fog | No Fog | | Fog | No Fog |
| Speed: 25 mi/h | Occlusion | .63 (.40) | .71 (.38) | Occlusion | .56 (.11) | .57 (.11) |
| | No Occlusion | .75 (.39) | .59 (.41) | No Occlusion | .55 (.11) | .52 (.12) |

*Note. N* = 47.

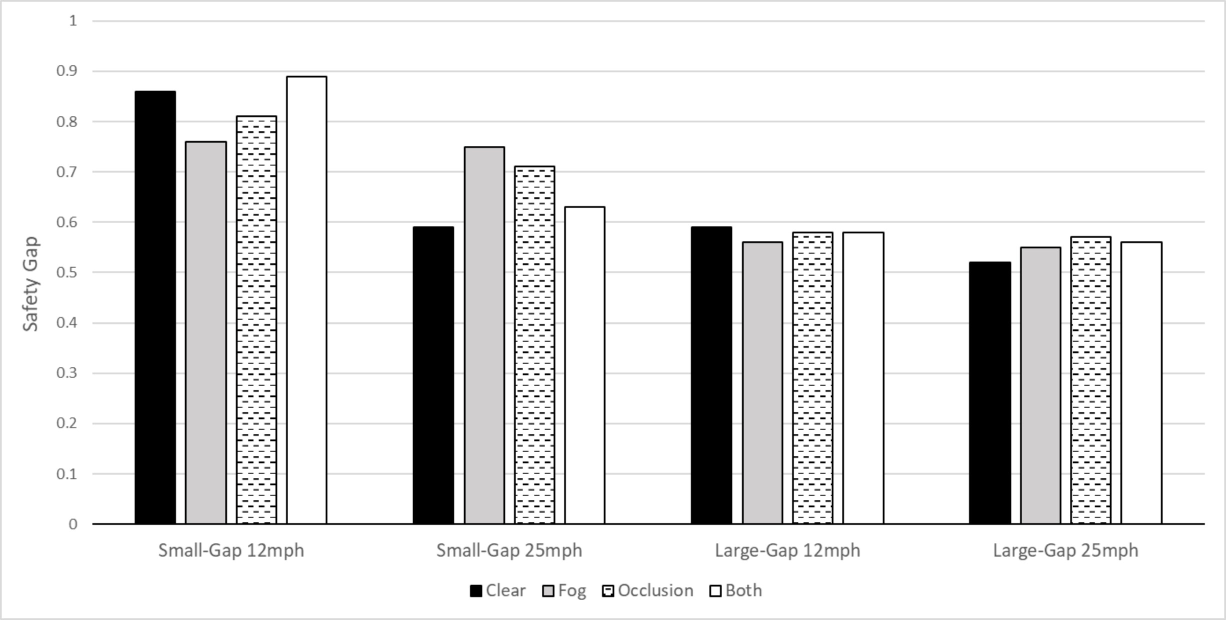


*Figure 3.2.* Mean safety gap across impairment conditions at each level of speed and disappearance time.

Table 3.3

*Means and standard deviations for perceptual and visuospatial performance variables.*

| | Visual Acuity | Contrast Sensitivity | Sound Localization | Corsi Score | Trail-Making Accuracy |
|---|---|---|---|---|---|
| Mean | 10 | 5.3 | 10.91 | 58.87 | 0.9 |
| SD | 1.41 | 0.7 | 1.12 | 16.71 | 0.1 |

*Note. N* = 47.

## Perceptual Variables

Pearson bivariate correlations were conducted to examine the relationships between perceptual variables and pedestrian task performance variables (time-to-contact and safety gaps). No significant correlations emerged.

### Time-to-contact

A fog (2) × occlusion (2) × disappearance time (2) × speed (2) repeated-measures ANOVA was conducted to test for differences between environmental visual impairment conditions in time-to-contact judgment errors. A significant main effect of disappearance time was found, $F(1, 46) = 116.39$, $p < .01$, partial $\eta^2 = .72$. A Bonferroni follow-up test indicated time-to-contact judgment errors were significantly smaller in the 3-second disappearance condition ($M = .90$, $SE = .06$) than in the 7-second disappearance condition ($M = 1.99$, $SE = .12$). No other significant main effects or interactions were found.

### Gap Selection

A fog (2) × occlusion (2) × gap size (2) × speed (2) repeated-measures ANOVA was conducted to test for differences between environmental visual impairment conditions in safety gaps. A significant main effect of speed was found, $F(1, 45) = 29.43$, $p < .01$, partial $\eta^2 = .39$. Pairwise comparisons revealed that safety gaps were significantly greater in the 12 mi/h condition ($M = .71$, $SE = .02$) than in the 25 mi/h condition ($M = .61$, $SE = .02$). A significant main effect of gap size was found, $F(1, 45) = 29.84$, $p < .01$, partial $\eta^2 = .40$. Pairwise comparisons revealed that safety gaps were significantly greater in the small gap condition ($M = .75$, $SE = .03$) than in the large gap condition ($M = .57$, $SE = .01$). A significant interaction between speed and gap size was found, $F(1, 45) = 7.73$, $p < .01$, partial $\eta^2 = .15$. Comparisons revealed the mean difference in safety gaps between gap sizes was larger in the 12 mi/h condition ($MD = .25$) than in the 25 mi/h condition ($MD = .12$). A significant interaction between speed, gap size, fog, and occlusion was found, $F(1, 45) = 10.24$, $p < .01$, partial $\eta^2 = .19$. Comparisons revealed the difference in safety gaps between levels of either type of impairment was larger in the 12 mi/h small gap condition ($MD = .04$) and 25 mi/h large gap condition (*MD* = .03) than in the other conditions. No other significant main effects or interactions were found.

Frequency data for virtual vehicle collisions and safe crossings are presented in Table 3.4. Overall, most collisions occurred in the small gaps condition, with minimal difference according to vehicle speed.

Table 3.4

*Frequencies for virtual vehicle collisions (successful crossings in parentheses) across impairment conditions at each level of speed and gap size.*

| | Small Gaps | | | Large Gaps | | |
|---|---|---|---|---|---|---|
| | | Fog | No Fog | | Fog | No Fog |
| Speed: 12 mi/h | Occlusion | 1 (14) | 5 (12) | Occlusion | 0 (90) | 1 (90) |
| | No Occlusion | 7 (10) | 4 (12) | No Occlusion | 1 (91) | 0 (92) |
| | | Fog | No Fog | | Fog | No Fog |
| Speed: 25 mi/h | Occlusion | 4 (27) | 3 (20) | Occlusion | 0 (92) | 0 (90) |
| | No Occlusion | 4 (13) | 7 (31) | No Occlusion | 0 (91) | 0 (91) |

*Note. N = 47; due to each gap selection trial being presented twice the maximum frequency for either type of occurrence (collision or safe crossing) is 94.*

The number of vehicles allowed to pass before enacting an action (successfully crossing or getting hit) was examined in a fog (2) × occlusion (2) × gap size (2) × speed (2) repeated-measures ANOVA testing for differences between environmental visual impairment conditions. A significant main effect of speed was found, *F*(1, 46) = 10.21, *p* < .01, partial $\eta^2$ = .18. Pairwise comparisons revealed that the mean number of passed cars was greater for the 12 mi/h condition (*M* = 3.92; *SE* = .12) than the 25 mi/h condition (*M* = 3.51, *SE* = .14). A significant main effect of gap size was found, *F*(1, 46) = 792.22, *p* < .01, partial $\eta^2$ = .95.

Pairwise comparisons revealed that the mean was greater for the small gaps condition (*M* = 5.95; *SE* = .16) than the large gaps condition (*M* = 1.48, *SE* = .11). A significant interaction was found between speed and gap size, *F*(1, 46) = 5.44, $p < .05$, partial $\eta^2 = .11$. Pairwise comparisons revealed that the mean difference between gap sizes was greater for the 12 mi/h condition (*MD* = 4.74) than the 25 mi/h condition (*MD* = 4.20). Descriptive data are presented in Figure 3.3.

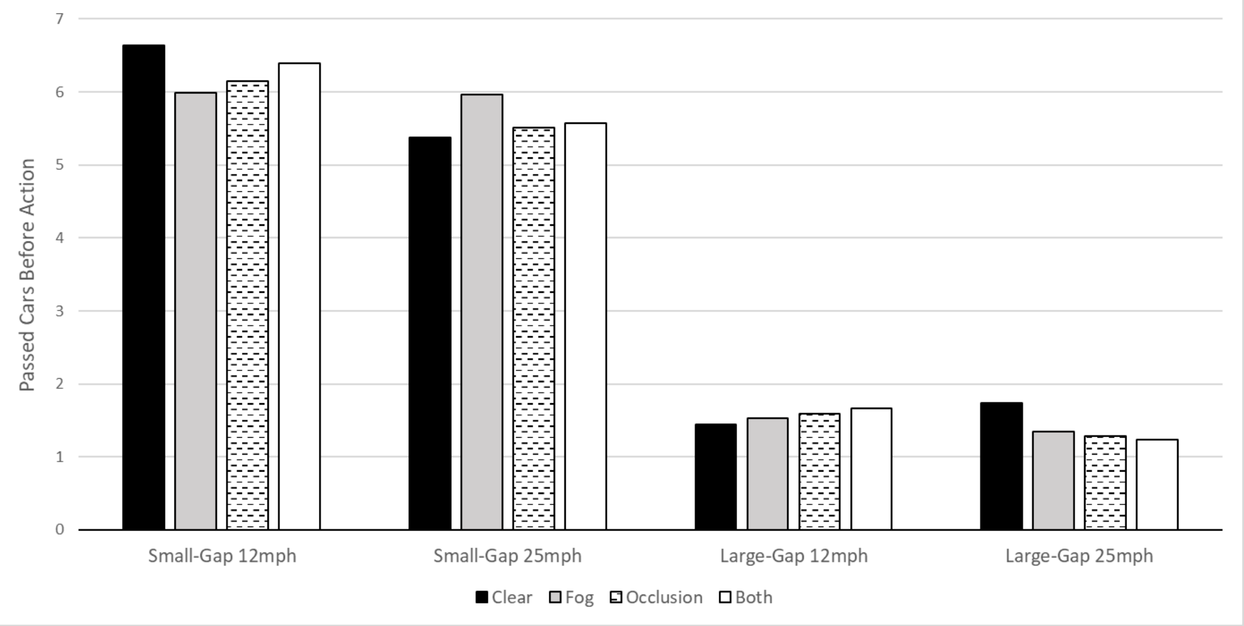


*Figure 3.3.* Mean number of vehicles allowed to pass before enacting an action across impairment conditions at each level of speed and gap size.

# Chapter 4: Discussion

My two studies represent an initial foray into how intrapersonal and environmental forms of perceptual impairment impact pedestrian safety. This line of inquiry was motivated by a scarcity of pedestrian safety literature systematically examining the roles of vision and audition in each stage of the pedestrian task (Davis, Pugliese, & Barton, 2019). By isolating vision and examining how different sources of impairment – such as alcohol intoxication or the presence of fog – can impact specific components of the pedestrian task such as time-to-contact estimation, I simultaneously addressed a critical gap in the pedestrian safety literature and set an example for how future studies may similarly give more thorough consideration to the dynamics of each perceptual modality.

## Study A

I found a significant effect of alcohol intoxication on estimates of vehicular time-to-contact. This provides the first (to my knowledge) empirical support for what has been suspected for decades via observational and archival research (e.g., Ulfarsson, Kim, & Booth, 2010). Indeed, a component of the pedestrian task being significantly impaired by intoxication parallels repeated findings that alcohol increases the risk of drivers getting into an accident (Irwin, Iudakhina, Desbrow, & McCartney, 2017). Additionally, I found significant differences only between the alcohol and control conditions. Participants who wore alcohol impairment goggles did not perform significantly differently than in either of the other two conditions. In other words, my results suggest the performance costs of alcohol intoxication, at least for the time-to-contact estimation component of the pedestrian crossing task, may stem more from cognitive impairment than from the perceptual effects of intoxication. At the same time, the implications of visual-only impairment producing results not significantly different from those produced by the combination of visual and cognitive impairments lends even more credence to the need for more perceptual modality-focused research in the pedestrian safety domain.

In terms of safety gaps and the number of vehicles the participant allowed to pass before either successfully crossing or getting hit, I did not find any significant effects of intrapersonal perceptual impairment. This finding makes sense from the perspective that making gap selections and crossing decisions constitutes a stage of the pedestrian task ostensibly well after oncoming traffic has been detected. In other words, making a curbside decision may be more of a cognitive task than a perceptual one, with perception's importance lying primarily in earlier aspects of the pedestrian task such as vehicle detection and time-to-contact estimation. At the same time, safety gaps and passing vehicles are only two ways of operationalizing the decision-making phase of the pedestrian crossing task. Of the participants who got "hit" by a virtual vehicle, nearly all were in the two intrapersonal perceptual impairment conditions, such that participants who experienced visual impairment via alcohol or goggles collectively had 2.64 times the risk of getting hit compared to participants in the control group. So while intrapersonal impairment may not have significantly impacted my two primary measures of gap selection, my results point toward this form of impairment leading to undesirable outcomes, suggesting intrapersonal sources of visual impairment such as alcohol may act on the pedestrian through mechanisms not examined in this study.

Another important factor to consider is that I used a target BAC of .05 (and similarly used goggles replicating the visual impairment associated with .04-.06 BAC). While this BAC is associated with visual perceptual deficits and mild cognitive impairment, the effects are qualitatively and quantitatively weak compared to higher levels of intoxication (such as .08

BAC, which is a common legal limit). Intrapersonal perceptual impairment in form of intoxication may therefore only significantly interfere with pedestrian decision making at higher BAC levels. While this study proved valuable in demonstrating a methodology for examining pedestrian behavioral variables in the context of alcohol intoxication and providing preliminary data for the effects of alcohol on two stages of the pedestrian task, more research is needed to understand how intrapersonal impairment arising from alcohol intoxication scales with BAC and extends to qualitatively different aspects of the pedestrian task. For example, how does visual impairment from alcohol intoxication affect the process of initial vehicle detection? Do environmental characteristics such the social context or crossing in a suburban versus urban setting interact with the effects of intrapersonal perceptual impairment?

Visuospatial performance, visual acuity, and contrast sensitivity neither significantly differing according to intrapersonal impairment condition nor being associated with time-to-contact or safety gap performance were somewhat surprising findings. Visuospatial working memory has been previously found to be associated with pedestrian visual search (Kovesdi & Barton, 2013). However, visual search is an aspect of pedestrian perception that ostensibly relates more to ascertaining the presence of traffic than making judgments and decisions based on vehicles whose presence is already known. Once again, the pedestrian task is complex, and the present set of studies only examined a few of the perceptual and cognitive processes people typically perform at crossing locations. Visuospatial performance, visual acuity, and contrast sensitivity may only become salient factors at certain stages of the pedestrian task and/or under certain contextual conditions. Additionally, alcohol’s effects on these variables (if any) may only become apparent at higher BACs which produce qualitatively and quantitatively stronger cognitive and perceptual decrements.

In Study A, vehicle disappearance time and gap size were significantly related to time-to-contact judgments and the number of cars allowed to pass respectively. These findings make intuitive sense: time-to-contact judgments were less accurate when participants had less time to spend looking and gleaning information about the oncoming vehicle before it disappeared, and larger gaps more readily afford a safe crossing opportunity than smaller gaps where more caution is warranted. More surprising, however, was the lack of any significant finding related to vehicle speed. Injury risk is known to scale monotonically with vehicle speed (Rosén, Stigson, & Sander, 2011), and previous work has found speed to be a significant factor in aspects of the pedestrian task such as time-to-contact estimates (e.g., Pugliese et al., 2020). The lack of significant variation according to vehicle speed may be attributable to the relatively small difference between the speeds I chose: 12 mi/h and 25 mi/h. The difference between these speeds may be less noticeable than between, for example, 5 mi/h and 25 mi/h, leading to participants treating them similarly.

## Study B

Contrary to my hypotheses, I did not find any significant effects of environmental sources of visual impairment (fog and the presence of an occluding tree) on time-to-contact judgments. One possible reason for this is that, like with intrapersonal perceptual impairment, the impact of environmental impairment may only become apparent under certain conditions or in certain stages of the pedestrian task. Intuitively, it makes sense for environmental conditions such as fog to not interfere strongly with the pedestrian task if the vehicle's presence is already known. However, given the inverse relationship between disappearance time (i.e., the amount of time the participant was allowed to spend looking and gleaning information from an approaching vehicle before it became imperceptible) and time-to-contact errors, the lack of significance for forms of environmental occlusion that can limit the visibility window of an approaching vehicle is somewhat surprising. Perhaps the presence of auditory information helps a pedestrian compensate for periods of limited visibility (Pugliese et al., 2020, found pedestrians to be capable of using auditory cues to make time-to-contact judgments, with the caveat of those judgments being significantly less accurate without visual information). Additionally, perhaps pedestrians engage in compensatory behavior such as paying closer attention to oncoming traffic and making more use of limited time if they are aware of a possible source of visual perceptual impairment.

Like with time-to-contact judgments, in Study B I did not find any significant effects of environmental perceptual impairment on measures of gap selection including safety gaps and the number of cars allowed to pass before either crossing or getting hit. Once again, I propose compensatory behavior and the lack of need to detect the presence of oncoming traffic to be possible explanations for environmental perceptual impairment's seemingly low relevance in the present study. Additionally, like with alcohol intoxication, any pedestrian task performance decrement brought about by factors such as fog or occluding objects may have to do with quantitative aspects of those factors. Specifically, I limited visibility to 100 m in my study, but in the real world visibility is often cut off at different distances, both further and closer. For example, fog can be relatively thin and only impede visibility at 300-500 m. Perhaps at these somewhat lower intensities people may be less likely to engage in compensatory behaviors. On the other hand, acute occlusion can often occur at much shorter distances than 100 m through mechanisms such as large parked vehicles. More work remains to be done to understand how quantitative aspects of environmental sources of visual impairment affect different stages of the pedestrian task.

Once again visuospatial performance, visual acuity, and contrast sensitivity were not significantly correlated with for either dependent measure. As I mentioned when discussing my findings related to intrapersonal visual impairment, visual search likely has more to do with vehicle detection than time-to-contact and gap selections. Visuospatial performance, visual acuity, and contrast sensitivity's relevance may only become apparent at certain stages of the pedestrian task and/or under certain contextual conditions. Just as with alcohol, environmental impairment's effects on these variables (if any) may only become apparent in qualitatively and quantitatively different conditions. For example, considering contrast sensitivity is a measure of a person's ability to identify visual stimuli at different levels of contrast, contrast sensitivity's relevance in the context of pedestrian environmental visual impairment may arise during the portion of the pedestrian task involving identifying visual stimuli (i.e., vehicle detection), especially in foggy conditions.

As with Study A, significant effects of disappearance time and gap size emerged for time-to-contact judgments and the number of cars allowed to pass respectively. Once again, time-to-contact judgment accuracy decreasing with the window of available information about the oncoming car makes sense. Similarly, participants allowing more cars to pass before either successfully crossing or getting hit – i.e., waiting longer – in the context of small gaps makes sense from the perspective of a pedestrian wishing to exercise extra caution when presented with heavy traffic.

Unique to Study B was the emergence of a significant interaction between speed and gap size for safety gaps (the proportion of the current gap between vehicles remaining at the moment the participant cleared the stream of traffic). Specifically, safety gaps were greater at 12 mi/h than at 25 mi/h, and this difference was larger for small gaps than for large gaps (additionally, safety gaps were larger for small gaps in general). This finding is somewhat surprising and can potentially be understood in terms of compensatory behavior. When presented with a large gap, there is less pressure on how a pedestrian times their crossing. Initiating a crossing slightly later than optimal can still result in a large margin of safety, and awareness of this fact may lead a pedestrian to initiate some crossings later than others and leave smaller safety margins. With small gaps (and subsequently less leniency for inopportune timing), the pedestrian may exercise more caution and strive to squeeze through the traffic gap early in its emergence. However, given that the vast majority of virtual vehicle collisions occurred in the small gap condition, the ability of such hypothetical compensatory behavior to actually compensate for the increased risk of collision inherent to smaller gaps is questionable. Larger safety gaps being associated with slower speeds may be due to timing a crossing being easier to manage when contending with slower vehicles.

An interaction between speed and gap size also emerged for the number of cars allowed to pass, but due to the relatively small magnitude of the difference between levels of speed at either level of gap size I hesitate to draw any conclusions regarding the meaningfulness of this particular result. More work is needed, especially research examining vehicle speeds greater than 25 mi/h.

## General Discussion

The relatively weak impacts of intrapersonal and environmental visual impairment observed in Studies A and B have interesting implications of pedestrian injury research and etiology. For example, the possibility that environmental impairment elicits compensatory behavior and extra caution raises the question of how the two forms of impairment interact. Specifically, how might perceptual impairment with a cognitive component, such as alcohol, impact a pedestrian’s ability to recognize hazardous environmental conditions and engage in compensatory behavior? Alcohol intoxication, especially BACs .08 or higher, is known to negatively impact decision making and risk perception. Given many pedestrian injuries occur in locations with higher densities of bars, there is a need for future work to examine the impacts of quantitatively different levels of intoxication, especially in varying environmental conditions.

Additionally, the present two studies examined participant populations without pre-existing uncorrected perceptual impairments. However, many pedestrians have auditory or visual impairments. Previous work (e.g., Ashmead et al., 2005) has found that blind pedestrians are able to adequately use auditory cues to inform their crossing conditions, but what is less clear is how forms of perceptual impairment impact populations with pre-existing impairments. For example, a pedestrian with normal vision may be able to compensate for the impairment posed by a foggy day, but a pedestrian with diminished visual sensory capabilities may experience a greater safety decrement in the same conditions.

The present studies provided valuable data on the relationship between visual perceptual traits – specifically visual acuity, contrast sensitivity, and visuospatial performance – and components of the pedestrian task. As mentioned previously, visual search is an important skill in the pedestrian task, and visuospatial working memory has previously been demonstrated to contribute to visual search performance in the pedestrian context (Barton, 2006; Kovesdi & Barton, 2013). The lack of a significant relationship between these visual perceptual variables, time-to-contact judgments, and gap selection stands as evidence that variables such as visual search may be more relevant to certain stages of the pedestrian task than others. Intuitively, visual search, contrast sensitivity, and visual acuity all make sense as perceptual skills important for the initial stage of vehicle detection.

In addition to implications for the scientific literature on pedestrian safety, my results have implications for injury prevention efforts as well. With what is to my knowledge the first empirical laboratory evidence of alcohol having a negative impact on pedestrian safety, an argument can be made for the creation of public awareness campaigns to discourage "drunk crossing." In Australia, the "Never Let a Mate Walk Home Drunk" campaign encourages friends of intoxicated pedestrians to assist their friend in getting home safely (Pedestrian Council of Australia, 2021). Further, just as the domain of drunk driving provided guidance for the design of the present research, it may provide guidance for injury prevention efforts in drunk pedestrian safety as well, with programs such as Mothers Against Drunk Driving serving as potential templates for pedestrian-oriented initiatives. A legislative approach, while theoretically possible using legislation against drunk driving as a template, may be too impractical to implement – a person drinking alone may not have any choice but to walk home alone.

No significant effects of fog or an occluding object were found. While the potential for these sources of visual impairment to be minimally relevant to pedestrian safety is promising, more research is needed to ascertain whether environmental impairment produces effects at different levels of intensity (e.g., proximity of occluding objects), at different stages of the pedestrian task (e.g., vehicle detection), or in conjunction with other forms of impairment (e.g., distraction or intoxication). If negative impacts of environmental impairment are eventually found, clear avenues for injury prevention from both legislative and public awareness perspectives would exist. Empirical evidence for safety costs of occlusion, such as via parked vehicles, would provide an impetus for stricter definition and enforcement of illegal parking zones to ensure pedestrian visibility is as clear as possible. A significant effect of ambient impairment, such as fog, could be mitigated by measures to increase vehicle detectability and ease of tracking, such as artificial noises and stricter enforcement of the requirement for drivers to turn their headlights on in fog. Public awareness campaigns could also expand the traditional wisdom of looking both ways before crossing a street to emphasize the need to be extra cautious under conditions of low visibility.

## Conclusion

Taken together, Studies A and B provide some of the first empirical data regarding how intrapersonal and environmental visual impairment impact pedestrian safety via performance on two stages of the crossing task, namely gap selection and estimating vehicular time-to-contact. Alcohol intoxication was found to decrease accuracy of time-to-contact judgments, while fog and a tree with occluding foliage did not produce significant effects on any measures of task performance. Visual acuity, contrast sensitivity, and visuospatial performance, variables known to be related to visual perception, were not affected by intrapersonal impairment.

Several considerations must be taken into account when interpreting the results of my studies. First, the set of vehicle stimuli I used was composed only of one vehicle traveling at two speeds and therefore cannot be considered a representative sample of all vehicles one might encounter on American roadways. Similarly, the forms of perceptual impairment in the two studies – alcohol intoxication and environmental sources of occlusion – were operationalized in categorical, isolated, dichotomous fashions. In the real world, people cross streets under various levels of intoxication, with varying degrees of visibility and vehicle types, and even while performing secondary tasks such as texting. Future studies should use a wider variety of vehicles to increase ecological validity, as well as manipulate perceptual impairments as continuous variables and in the context of secondary tasks. Further integration of a human factors perspective may prove useful in pursuing a more thorough understanding of the factors which may impact pedestrian safety – for example, human reliability analysis methods are commonly used to identify factors which can influence the probability of human error in domains such as nuclear power plant process control (e.g., Boring, 2010). Classic examples of such performance-shaping factors include task complexity, mental workload, and environmental conditions, all of which are applicable in a pedestrian safety context.

Second, the samples were comprised mostly of young adults with normal visual and auditory perceptual abilities from a university community and were therefore not representative of the population at large. Further, the sample sizes may have been two small to detect significant differences in indices of task performance brought about by the intrapersonal and environmental forms of impairment (with the sole exception of the alcohol condition in Study A). While the sample sizes I used were established via a priori power analyses, said power analyses were based on effect sizes observed in the driving safety literature and may not be appropriate for the pedestrian crossing context. Both studies were conducted during the COVID-19 pandemic and therefore may have recruited qualitatively and quantitatively different samples than would have been recruited in a different public health climate. Future studies should recruit larger and broader samples to respectively increase statistical power and examine how factors such as age interact with various forms of perceptual impairment, as has already been done to some degree in the driving safety literature (e.g., Trick, Lochner, Toxopeus, & Wilson, 2017).

Finally, since my studies justifiably focused on two stages of the pedestrian crossing task in the context of the visual modality, there is room for future studies to examine other task stages (e.g., vehicle detection) as well as the impacts of various forms of auditory perceptual impairment. Some auditory impairment work has already been done with environmental factors such as competing vehicle noises (Ulrich, Barton, & Lew, 2014), but little is known, for example, about how alcohol affects pedestrian safety in auditory-dominant contexts.

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## Appendix A: Luebeck Alcohol Dependence and Abuse Screening Test

The following questions are to be answered in a yes/no manner by the participant. Answering question 1 with "no" or any other question with "yes" results in the addition of one point to the participant's score. Scoring more than one point is typically interpreted as a possible sign of alcohol dependence or abuse.

*Are you always able to stop drinking when you want to?*

*Have you ever felt you should cut down on your drinking?*

*Have you ever felt bad or guilty about your drinking?*

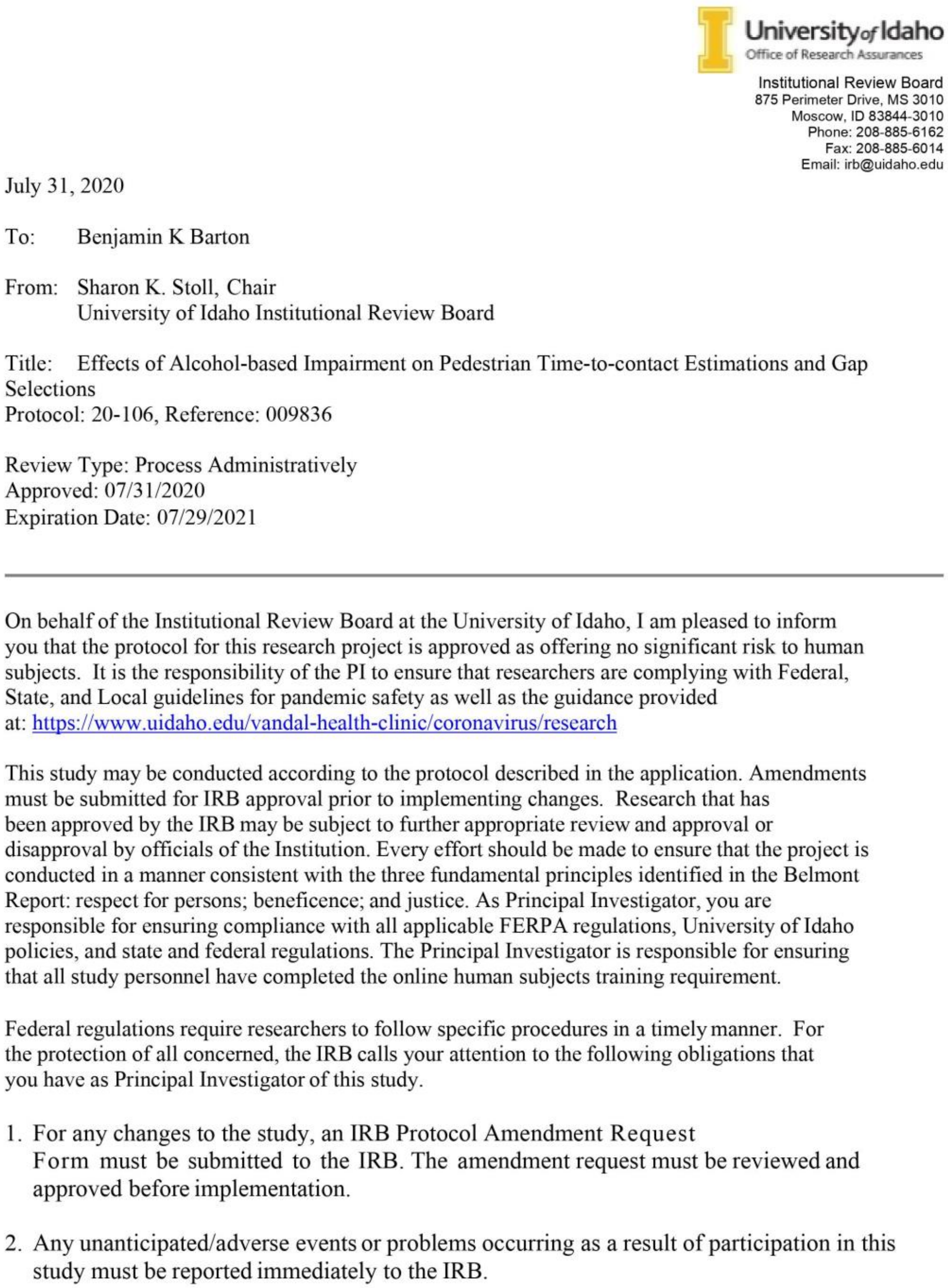
*Does your significant other, a parent, or other near relative ever worry or complain about your drinking?*

*Have you ever gotten into trouble at work because of drinking?*

*Have you ever been told you have liver trouble? Cirrhosis?*

*Have you ever been in a hospital because of drinking?*

# Appendix B: Study A IRB Approval



University of Idaho
Office of Research Assurances

Institutional Review Board
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July 31, 2020

To: Benjamin K Barton

From: Sharon K. Stoll, Chair
University of Idaho Institutional Review Board

Title: Effects of Alcohol-based Impairment on Pedestrian Time-to-contact Estimations and Gap Selections
Protocol: 20-106, Reference: 009836

Review Type: Process Administratively
Approved: 07/31/2020
Expiration Date: 07/29/2021

---

On behalf of the Institutional Review Board at the University of Idaho, I am pleased to inform you that the protocol for this research project is approved as offering no significant risk to human subjects. It is the responsibility of the PI to ensure that researchers are complying with Federal, State, and Local guidelines for pandemic safety as well as the guidance provided at: https://www.uidaho.edu/vandal-health-clinic/coronavirus/research

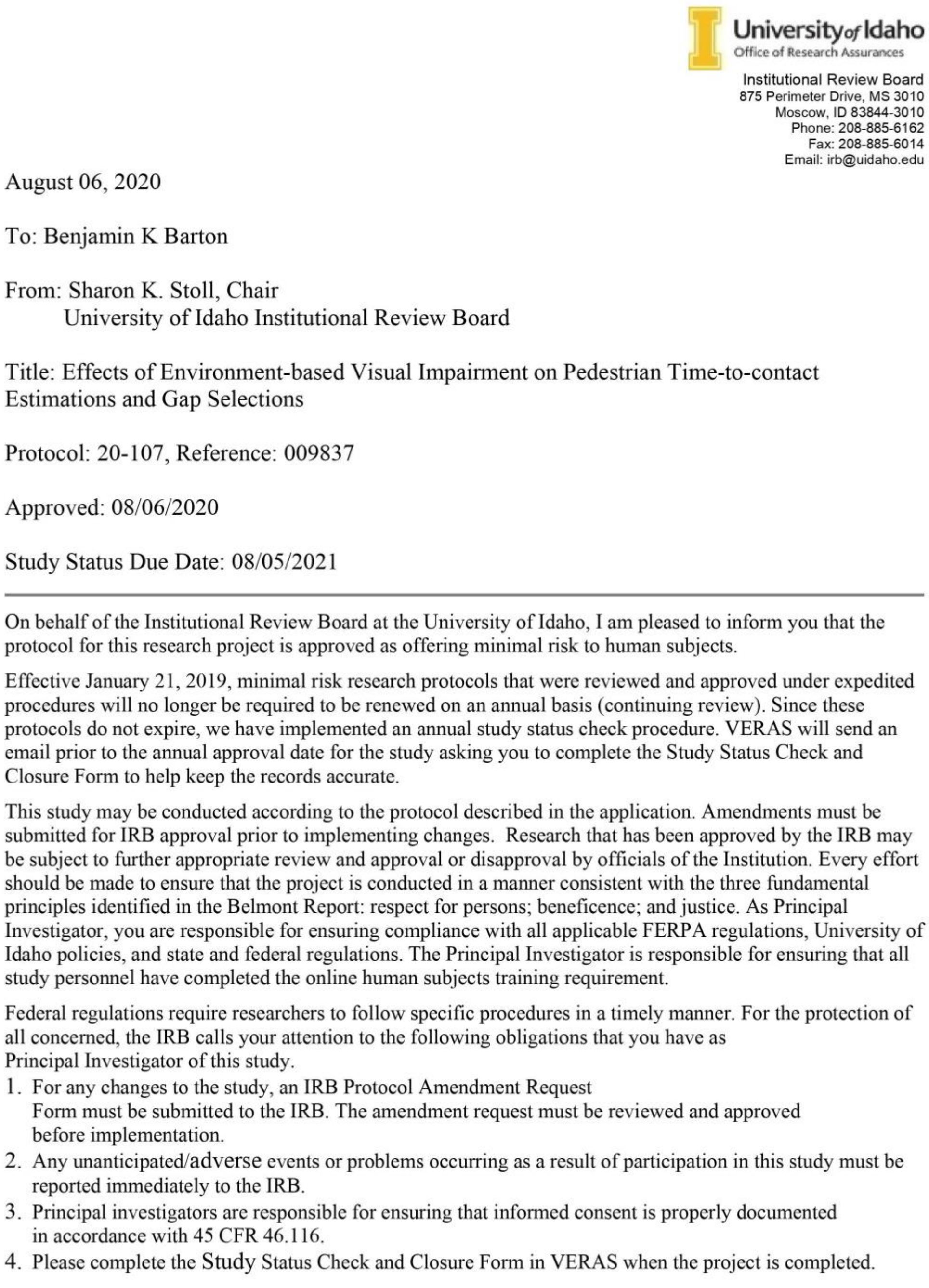
This study may be conducted according to the protocol described in the application. Amendments must be submitted for IRB approval prior to implementing changes. Research that has been approved by the IRB may be subject to further appropriate review and approval or disapproval by officials of the Institution. Every effort should be made to ensure that the project is conducted in a manner consistent with the three fundamental principles identified in the Belmont Report: respect for persons; beneficence; and justice. As Principal Investigator, you are responsible for ensuring compliance with all applicable FERPA regulations, University of Idaho policies, and state and federal regulations. The Principal Investigator is responsible for ensuring that all study personnel have completed the online human subjects training requirement.

Federal regulations require researchers to follow specific procedures in a timely manner. For the protection of all concerned, the IRB calls your attention to the following obligations that you have as Principal Investigator of this study.

1. For any changes to the study, an IRB Protocol Amendment Request Form must be submitted to the IRB. The amendment request must be reviewed and approved before implementation.

2. Any unanticipated/adverse events or problems occurring as a result of participation in this study must be reported immediately to the IRB.

# Appendix C: Study B IRB Approval



University of Idaho
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August 06, 2020

To: Benjamin K Barton

From: Sharon K. Stoll, Chair
University of Idaho Institutional Review Board

Title: Effects of Environment-based Visual Impairment on Pedestrian Time-to-contact Estimations and Gap Selections

Protocol: 20-107, Reference: 009837

Approved: 08/06/2020

Study Status Due Date: 08/05/2021

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On behalf of the Institutional Review Board at the University of Idaho, I am pleased to inform you that the protocol for this research project is approved as offering minimal risk to human subjects.

Effective January 21, 2019, minimal risk research protocols that were reviewed and approved under expedited procedures will no longer be required to be renewed on an annual basis (continuing review). Since these protocols do not expire, we have implemented an annual study status check procedure. VERAS will send an email prior to the annual approval date for the study asking you to complete the Study Status Check and Closure Form to help keep the records accurate.

This study may be conducted according to the protocol described in the application. Amendments must be submitted for IRB approval prior to implementing changes. Research that has been approved by the IRB may be subject to further appropriate review and approval or disapproval by officials of the Institution. Every effort should be made to ensure that the project is conducted in a manner consistent with the three fundamental principles identified in the Belmont Report: respect for persons; beneficence; and justice. As Principal Investigator, you are responsible for ensuring compliance with all applicable FERPA regulations, University of Idaho policies, and state and federal regulations. The Principal Investigator is responsible for ensuring that all study personnel have completed the online human subjects training requirement.

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1. For any changes to the study, an IRB Protocol Amendment Request Form must be submitted to the IRB. The amendment request must be reviewed and approved before implementation.
2. Any unanticipated/adverse events or problems occurring as a result of participation in this study must be reported immediately to the IRB.
3. Principal investigators are responsible for ensuring that informed consent is properly documented in accordance with 45 CFR 46.116.
4. Please complete the Study Status Check and Closure Form in VERAS when the project is completed.