Final Report: Aging Road User, Bicyclist, and Pedestrian Safety: Effective Bicycling Signs and Preventing Left-Turn Crashes BDK83 977-15

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Disclaimer

SI* (Modern Metric) Conversion Factors

Approximate Conversions to SI Units

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
floz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	pound force	4.45	newtons	N
lbf/in^2	pound force per square inch	6.89	kilopascals	kPa
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**

LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	floz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
^oC	Celsius	1.8C+32	Fahrenheit	^oF
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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16. Abstract. Task 1 assessed younger, middle-aged, and older drivers' knowledge of various bicycle warning signs and pavement markings, finding: 1) In general, knowledge was high, 2) Some pavement markings and signs were frequently misunderstood even among bicyclists (i.e., Sharrow, Bicycle Detector markings and Bicyclist Slippery when Wet sign), 3) Share the Road and 3 Foot Minimum signs were generally more quickly understood and recognized in versions of the sign depicting a sideways view of a bicycle rather than a rear view of a bicyclist/bicycle, and 4) Tests with blurred versions of these signs also suggested a legibility advantage for signs depicting a sideways view of a bicycle. In Task 2, we explored whether these differences in comprehension/recognition/legibility had an impact on driver behavior in a simulator study. Younger, middle-aged, and older drivers navigated a simulated route in which they passed bicyclists riding singly or in groups. Sometimes bicyclists were located within a bike lane, and sometimes a bike lane was not present. The main findings were: 1) Drivers generally passed bicyclists with care, allowing a clearance much greater than 3 feet, 2) Groups of bicyclists were given more clearance compared to single bicyclists, 3) Passing distances were smaller in the presence of oncoming traffic, 4) Passing distances were smaller when a bike lane was present, 5) The type of sign and the presence of a sign with the message to give bicyclists at least 3 feet of clearance did not impact passing distances, and 6) Age did not have a significant impact on passing distances. Finally, Task 3 examined whether decreased negative offset (minimal offset) left-turn lanes provided a safety advantage to drivers of all ages. Drivers first completed a gap judgment task in the driving simulator (Task 3a). In Task 3b, participants drove a simulated route and were asked to make turns at intersections featuring a minimal or large negative offset. Findings were as follows: 1) No differences between minimal and negative offsets were observed in the gap judgment task, 2) Younger adults tolerated smaller gaps in traffic compared to older adults, 3) The minimal offset resulted in a benefit in the turn execution task; turns were executed in such a way that the distance between the drivers' cars and oncoming traffic was larger compared to the negative offset condition. We conclude that: 1) educational campaigns focused on the meaning of certain bicycle-related pavement markings and signs may be beneficial, 2) although passing distance was not influenced, Share the Road signs and 3 Foot Minimum signs should feature a side profile of a bicycle to facilitate comprehension, 3) Decreasing negative offset of left-turn lanes is an effective means to encourage safer left turns for drivers of all ages.

17. Key Word	18. Distribution Statement		
Bicyclist, pedestrian, left turn, older driver, age, turn lane offset, aging road user	No restrictions		
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Executive Summary

The following report investigated the effectiveness of safety countermeasures designed to protect two types of vulnerable road users: 1) Bicyclists, whose vehicles provide little protection in the event of a crash with a motor vehicle, and 2) Older adults, who are more vulnerable to crash forces and whose perceptual and cognitive abilities, due to age-related cognitive decline, make the driving task more challenging. These issues are especially relevant for the state of Florida, given its large and growing older adult population and the fact that Florida is the state with the highest bicyclist fatality rate in the United States. The Florida Department of Transportation (FDOT) will use study results to support the implementation of the Aging Road User Strategic Safety Plan.

In order for signs and pavement markings indicating the presence of bicyclists to be effective, bicyclists and older adults must accurately and quickly recognize and comprehend them as well as understand how a driver should modify his or her behavior in response to the presence of bicyclists. Task 1 focused on bicyclist (and pedestrian) related signs and pavement markings, and how quickly younger (ages 21 to 35), middle-aged (ages 50 to 64), and older adults (ages 65 and older) could understand their meaning and recognize them at near (10 to 20 feet), middle (75 to 198 feet), and far (198 to 502 feet) distances. Performance in an untimed test of participants' knowledge of each sign and pavement marking was also assessed. In general, younger, middle-aged, and older adults exhibited a high level of knowledge about signs with some notable exceptions. Participants, including bicyclists, experienced difficulty understanding the Sharrow pavement marking and the Bicycle Detector marking (indicating where bicyclists should position themselves in order to trigger the traffic signal to change). The bicyclist version of the Slippery when Wet sign was also poorly understood, especially by younger adults. Two versions of the signs 3 Foot Minimum and Share the Road were tested (which differed in that one version showed a profile view of a bicycle and the other showed a bicyclist viewed from behind) and were generally well understood. However, the versions of these signs that featured a profile of a bicycle tended to be more quickly understood and identified.

Task 2 studied the impact of three different bicycle warning signs on driver passing distance from bicyclists in a driving simulator task. Participants encountered bicyclists after being presented with one of two different versions of the 3 Foot Minimum sign or a Share the Road sign. A bike lane was either present or absent when the driver encountered a single bicyclist or group of bicyclists. Bicycle warning sign presence and sign type did not have an impact on passing distances; drivers of all ages tended to pass bicyclists with care; on average, drivers in all age groups gave cyclists over 6 feet of space. Finally, consistent with previous research (e.g. Parkin & Meyers, 2010), passing distances were smaller, 4.74 feet on average, when an oncoming car was present in the opposing lane and greater for a group of bicyclists (M = 6.85 feet, SD = 1.58 feet) compared to a single bicyclist (M = 5.99 feet, SD = 1.36 feet). Finally, also consistent with previous research (e.g. Parkin & Meyers, 2010) passing distances were smaller when the bicyclist was within a bike lane (M = 6.23, SD = 1.46) than when they were not within a bike lane (M = 6.60, SD = 1.60). As bike lanes have generally been found to improve safety, the source of this benefit seems to be something other than greater passing distance.

Finally, Task 3 examined a countermeasure that has been designed and implemented to reduce left-turn crashes. Older drivers are at higher risk for this type of crash, and when a crash does occur, older adults are more likely to be seriously injured or killed. Decreasing the negative offset of left-turn lanes so that the opposing left-turn lane is shifted to the right has been proposed to reduce left-turn crashes. Shifting opposing turn lanes to the right allows the driver a better view of oncoming traffic and may result in better speed and distance estimates of oncoming vehicles. However, not all studies have found a benefit. Younger, middle-aged, and older drivers participated in a simulator study in which they first judged whether it was safe to turn (Task 3a) and then in a second segment of the session actually executed left turns (Task 3b). Younger adults were more willing to make riskier turns (turns that would place their vehicle closer to oncoming traffic). Furthermore, in the left-turn execution task, minimal offset left turns provided a significant safety advantage for drivers of all ages by causing drivers to accept larger gaps in traffic. Data suggest, though, that this advantage was diminished for older adults when oncoming vehicles were moving at a faster speed. Future research is needed to confirm the latter trend.

Based on these findings, we offer a number of recommendations:

1) Educational campaigns have the potential to increase understanding of bicycle-related signs and pavement markings. Although in general, drivers displayed accurate knowledge of 3 Foot Minimum and Share the Road signs, accurate knowledge was not universal. Bicycle safety educational materials, including the *Florida Bicycling Street Smarts* booklet, Florida's Driver Handbook, and similar materials should be updated to feature an explanation of markings and signs that even active bicyclists found confusing. These signs and markings include the bicyclist Slippery when Wet sign and the Sharrow and Bicycle Detector pavement markings.

2) We recommend versions of the 3 Foot Minimum and Share the Road signs featuring the depiction of a sideways profile of a bicycle compared to the rear view of a bicyclist/bicycle.

3) We recommend that future studies begin to assess passing distance (with and without bicycle warning signs) under more challenging conditions than those studied in this project (e.g., high traffic, narrower lanes, poor visibility, conditions of distraction). We recommend that more research is needed to better understand the mechanism responsible for increased safety when a bike lane is present, as such understanding may allow for even more effective countermeasures to be developed. The mechanism does not appear to be related to encouraging greater passing distances.

4) We found, consistent with some but not all of the literature, that minimal offset left-turn lanes (that did not result in a full positive offset) were beneficial to drivers of all ages. When possible, and when relevant (e.g., offset probably has a minimal impact on protected turns), minimal offset or positive offset left-turn lanes should be implemented. Our data suggested that, at least for older adults, the benefit of minimal offset lanes may be diminished when traffic is moving quickly. If additional research confirms this pattern, it would suggest that protected turn lanes or other intersection configurations such as roundabouts may be more beneficial to aging road users in some situations.

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Chapter 1.

Introduction

The roadway environment should be designed to protect vulnerable road users of all types. This includes designing with the aging road user in mind because older drivers are at higher risk for injury and death as a result of a crash. Bicyclists can also be considered vulnerable road users because, unlike drivers, their vehicles provide little protection in the event of a crash. These issues are especially relevant to the state of Florida with its aging population and large bicyclist community. Moreover, a recent analysis of bicycling fatalities from 2008 revealed Florida as the national outlier with three times the national rate of bicycling-related fatalities (Ackery, McLellan, & Redelmeier, 2012).

Unfortunately, while overall U.S. traffic fatalities have been trending downward in the past decade (42,000 in 2002, compared to 32,000 in 2011), in this same period the percent of fatalities accounted for by bicyclist fatalities involving a motor vehicle has increased from 1.5% to 2.1% (NHTSA, 2013). Bicyclist safety is of special interest to the state of Florida. According to NHTSA (2013), in 2011 more bicyclists were killed in Florida compared to any other state, with bicyclist fatalities accounting for 5.2% of all traffic fatalities in Florida. Nationally, and of particular relevance to Florida's aging road user program, "Safe Mobility for Life," bicyclist fatalities affect all age groups (about 13% of all fatal bicycle crashes involve bicyclists age 65+). The average age of a bicyclist killed in a crash increased 7 years in the past decade to 43 years old. In addition to the hundreds of bicyclist fatalities in 2011 in the U.S., there were many more bicyclists injured in crashes involving a motor vehicle (about 48,000). National and state-level statistics indicate that there is a need to investigate the causes of crashes involving bicyclists and methods to reduce the incidence and severity of these crashes.

Perhaps not surprisingly, traffic-related fatalities and serious injuries occur more frequently at or near intersections, and the type of crash most likely to result in serious injury is the left-turn crash. A left-turn crash involves a driver turning across a (typically fast-moving) stream of traffic and being struck by opposing traffic during the turn. As we will review later, older adults find making left turns especially challenging due to age-related changes to cognition and vision. Also, due to increased vulnerability to crash forces, older drivers are more likely than younger drivers to be seriously injured or killed when involved in a vehicle crash (e.g. Li, Braver, & Chen, 2003). Countermeasures to reduce left-turn crashes have the potential to substantially reduce the higher risk experienced by older drivers.

The series of studies outlined in this report had the aim of understanding the effectiveness of various countermeasures designed to increase the safety of two types of vulnerable road-users: bicyclists and older adults. Effective countermeasures are anticipated to be especially beneficial to Florida because 1) Florida has the highest bicyclist fatality rate in the nation, 2) Florida has one of the oldest populations in the

U.S., with 18% of its population estimated to be age 65 or older, and the number of older citizens in Florida and throughout the nation is predicted to continue to grow (U.S. Census Bureau, 2011), and 3) research-based decision making is needed to support our Aging Road User Strategic Safety Plan. More generally, educating drivers about how to safely share the road with cyclists should have the effect of making bicycling safer and may additionally have the potential to encourage an alternative form of transportation associated with benefits both for personal health and for the environment. Furthermore, countermeasures to bring the abilities of the older driver back into alignment with the driving environment have the potential to prolong older adults' independence.

Objectives and Supporting Tasks

Task 1 focused on the best ways to convey bicycle-related messages to drivers. A goal of this research project was to understand drivers' knowledge of bicycle warning signs and pavement markings. The outcome of this project has the potential to guide development of educational materials to reduce confusion about the meanings of signs and pavement markings, or to guide the design of alternative markings and signs that might better convey their intended message. This task involved 1) testing drivers' knowledge of signs and pavement markings, 2) assessing the speed with which a sign or marking could be comprehended, and 3) assessing the perceptibility of signs at different distances. Younger, middle-aged, and older drivers were tested in this laboratory-based task (in all studies, younger adults were individuals between the ages of 21 and 35, middle-aged adults were between the ages of 50 and 64, and older adults were 65 and above). Special interest was paid to the best bicycle warning signs with which to convey the message that in the state of Florida, a motorist must pass a bicyclist with at least three feet of clearance.

Task 2 focused on driver behavior toward bicyclists. The results of Task 1 were used to develop driving simulator scenarios in which younger, middle-aged, and older drivers passed single or groups of bicyclists after encountering one of three bicycle warning signs. We also assessed the impact of bike lanes on drivers' passing distances and monitored their eye movements to understand their allocation of attention to signs and bicyclists.

Finally, Task 3 addressed the issue of left-turn crashes. Specifically, this driving simulator study assessed the effectiveness of decreased negative offset left-turn lanes in inducing safer driving performance in younger, middle-aged, and older adults. As we will review later, this countermeasure has not always been found to be effective. The goal was to provide additional evidence in favor of or against the effectiveness of this countermeasure designed to reduce the number of left-turn crashes.

The findings from these studies provide critical information about the conditions surrounding bicyclist and older adult crashes, which will aid FDOT in developing appropriate guidelines and recommendations for the design and implementation of countermeasures. In addition, findings from these studies can be used to guide the design of education programs for both drivers and bicyclists to better inform the public about safe navigation of the roadway.

Chapter 2

Task 1: Perception and comprehension of bicycle warning signs and pavement markings.

To ensure that drivers of all ages safely navigate the roadway in the presence of bicyclists and pedestrians, the signs and pavement markings conveying the potential presence of bicyclists/pedestrians and how a driver should modify his or her behavior when encountering them need to be quickly and accurately understood. To help achieve this goal, Task 1 assessed younger, middle-aged, and older drivers' knowledge of pedestrian and bicycle warning signs (both existing and proposed signs) and pavement markings, as well as their ability to quickly recognize their meaning.

Method

Participants

A total of 68 participants from the Tallahassee, FL area were recruited. All were licensed drivers who drove at least once a week. This sample included 48 non-cyclists (18 younger, *Mean Age* = 23; 13 middle-aged, *Mean Age* = 57; 17 older adults*, Mean Age* = 71), and 17 bicyclists of varying ages (14 younger, 2 middle-aged, and 1 older, *Mean Age* = 30). A participant was considered a bicyclist if he or she reported bicycling more than 5 miles per week. Participants were paid 15 dollars for their participation or received course credit if they were enrolled at Florida State University.

Materials

The bicycle warning signs and pavement markings tested were either taken from the Manual on Uniform Traffic Control Devices (MUTCD) or provided to us by FDOT. Figure 1 displays the bicycle and pedestrian-related signs, and Figure 2 displays bicycle-related pavement markings that were part of Task 1.

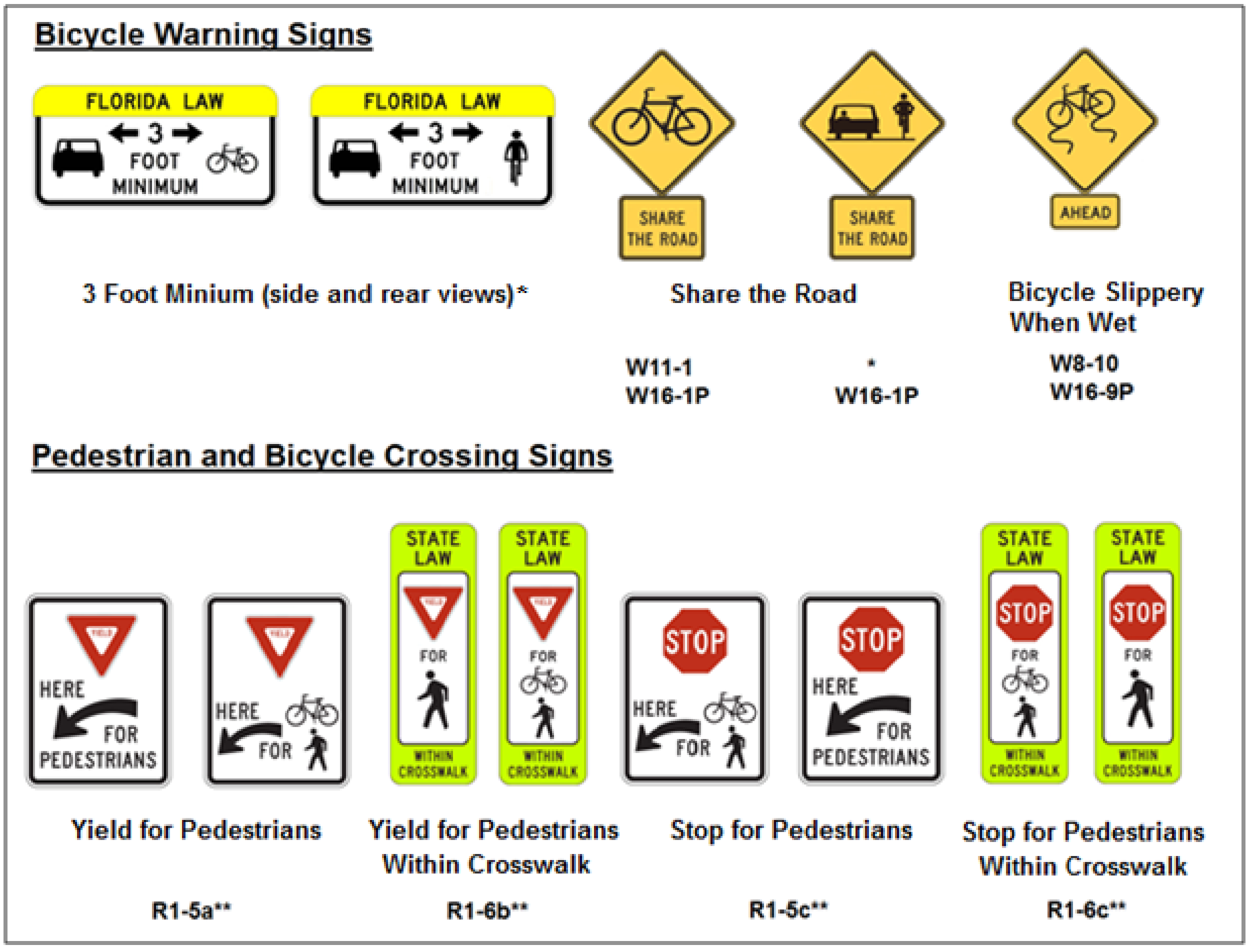

Figure 1. Bicycle and pedestrian warning signs tested as part of Task 1.
** Sign does not have a MUTCD sign number.*
*** Versions of these signs featuring a bicyclist and pedestrian together do not have a MUTCD sign number.*

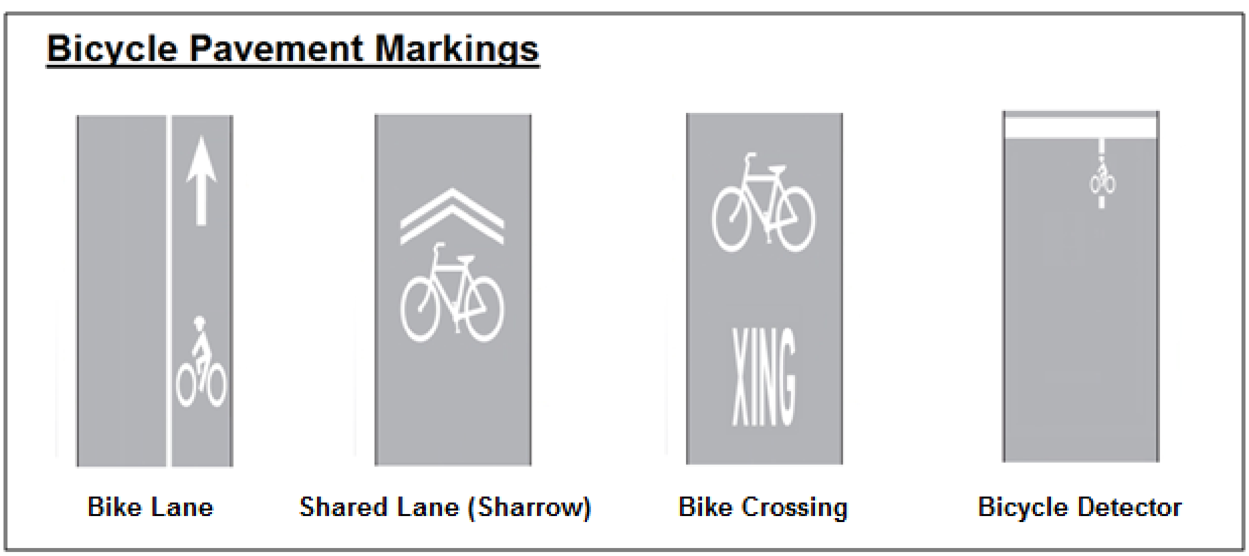

Figure 2. Bicycle pavement markings tested as part of Task 1.

This sign set included an experimental sign featuring the sideways view of a bicycle in the context of a 3 Foot Minimum message (Figure 1, 3 Foot Minimum (Side)). This sign typically depicts a car to the left and a bicyclist/bicycle riding away from the observer to the right (Figure 1, 3 Foot Minimum (Rear view)). A concern is that the traditional depiction of the bicycle/bicyclist might not be easily recognized because the orientation of the bicyclist/bicycle makes the rider and bicycle difficult to recognize.

Procedure

Task 1 consisted of three different phases. First, participants completed a sign knowledge task in which they were shown a sign or pavement marking on an LCD computer screen and were asked to provide its meaning (free response). All signs and markings were presented at the closest simulated distance (see Table 1). Once participants provided meanings for all items they were shown the correct meaning for each sign and pavement marking.

The second and third parts of Task 1 consisted of a pattern matching and a sign comprehension task. The order in which these two tasks were completed was varied such that half of the participants in each age group completed the pattern matching task second and the sign comprehension task third, and the other half completed the sign comprehension task second and the pattern matching task third. This was done to control for administration order effects, the concern that experience with one task may affect performance on the other.

The pattern matching task was speeded; participants were instructed to respond as quickly and accurately as possible and were also instructed to leave their fingers on the response keys to facilitate quick responding. In this task, participants were shown pairs of signs or pavement markings sequentially and asked to indicate, as quickly as possible, whether the second sign or marking was the same or different from the first by pressing one of two keys (one marked “same” and the other marked “different”). Signs were always paired with signs and pavement markings were always paired with pavement markings, and these two item types were presented in separate blocks. Signs were presented at three simulated distances. For example, the first sign displayed could be “bicycle crossing” at a simulated viewing distance of 20 feet followed by the “bicycle crossing” sign or a different sign (foil) at 502 feet. Pilot testing and physical sign size determined the three distances tested (see Table 1). Viewing distance was not manipulated for pavement markings.

In the comprehension task, participants were presented with the meaning of a sign or pavement marking followed by the image of either the same or a different sign or pavement marking. Participants were instructed to indicate, as quickly and accurately as possible, whether or not the presented meaning matched the presented sign. As in the pattern matching task, signs were presented at one of three simulated viewing distances.

All participants completed the sign knowledge task first, but the order of the pattern matching and comprehension tasks were varied between participants. For all three tasks, items were presented in a random order.

Table 1. Simulated distances of signs for Task 1.
** Sign does not have a MUTCD sign number.*
*** Versions of these signs featuring a bicyclist and pedestrian together do not have a MUTCD sign number.*

			Simulated distance (feet)		
Bicycle Warning Sign	**MUTCD**	**Original Size(in)**	**Near**	**Middle**	**Far**
3 Foot Minimum (Side)*	--	--	20	75	198
3 Foot Minimum (Rear View)*	--	--	20	75	198
Share the Road (Side)	W11-1 / W16-1P	36 x 36	20	198	502
Share the Road (Rear View)*	-- / W16-1P	36 x 36	20	198	502
Bicycle Slippery when Wet	W8-10 / W16-9P	36 x 36	20	198	502
Pedestrian and Bicyclist Crossing	**MUTCD**	**Sign Size**	**Near**	**Middle**	**Far**
Yield for Pedestrians	R1-5a	36 x 48	20	75	198
Yield for Pedestrians and Bicycles	R1-5a**	36 x 48	20	75	198
Yield for Pedestrians (Crosswalk)	R1-6b	12 x 36	10	75	198
Yield for Pedestrians and Bicycles (Crosswalk)	R1-6b**	12 x 36	10	75	198
Stop for Pedestrians	R1-5c	36 x 48	20	75	198
Stop for Pedestrians and Bicycles	R1-5c**	36 x 48	20	75	198
Stop for Pedestrians (Crosswalk)	R1-6c	12 x 36	10	75	198
Stop for Pedestrians and Bicycles (Crosswalk)	R1-6c**	12 x 36	10	75	198

Results

Sign Knowledge

Participants were presented with 17 signs/pavement markings and were required to provide their meaning. Of primary interest was accuracy. Two raters judged the accuracy of each response. To determine the consistency between raters, an inter-rater reliability analysis was performed. Kappa, a test of inter-rater agreement, was found to be .63, indicating substantial agreement between the two raters (Landis & Koch, 1977). In subsequent analysis, an answer was scored as correct if both raters agreed that it was correct. A similar pattern of results was obtained when each rater's ratings were considered separately.

First, a chi-square test was performed on data from each sign/pavement marking to determine whether knowledge differed as a function of group (Younger, Middle-Aged, Older, and Bicyclist). In general, no significant differences were found, suggesting that regardless of age or bicyclist status, knowledge was similar (Table 2). One exception was the Slippery when Wet bicycle warning sign, which will be discussed later. However, given the generally similar performance of all groups we present data collapsed across age and bicyclist status.

Table 2. Chi-square tests exploring whether or not age or cycling experience influenced accuracy in the Sign Knowledge task.
Degrees of freedom for all tests are 3. N = 68.

Bicycle Warning Signs	X^2	*P*
3 Foot Minimum (Side)	3.38	0.34
3 Foot Minimum (Rear view)	1.71	0.64
Share the Road (Side)	1.16	0.76
Share the Road (Rear view)	2.63	0.45
Bicycle Slippery when Wet	9.97	<.05
Pedestrian and Bicyclist Crossing Signs		
Yield for Pedestrians	3.66	0.30
Yield for Pedestrians and Bicycles	6.24	0.10
Yield for Pedestrians(Crosswalk)	1.83	0.61
Yield for Pedestrians and Bicycles (Crosswalk)	3.78	0.29
Stop for Pedestrians	3.71	0.29
Stop for Pedestrians and Bicycles	4.71	0.19
Stop for Pedestrians (Crosswalk)	2.60	0.46
Stop for Pedestrians and Bicycles (Crosswalk)	1.15	0.76
Bicycle Pavement Markings		
Bike Lane	0.96	0.81
Bike Crossing	0.05	0.99
Sharrow	1.91	0.59
Bicyclist Detector	0.00	0.99

Figure 3 represents accuracy of responding for each bicycle warning sign, including the two versions of the 3 Foot Minimum sign, and two versions of the Share the Road sign. A chi-square analysis revealed that accuracy was significantly different between the five bicycle warning signs ($X^2(4, N = 340) = 64.96, p<.001$). This was driven by the bicyclist-oriented Slippery when Wet sign being relatively poorly understood (no significant difference was observed between bicycle warning signs when this sign was removed from analysis ($X^2(3, N = 272) = 6.29, p = .10$). Participants often mistook the meaning of the Slippery when Wet sign as indicating a curvy or winding road was ahead, a bicyclist path was ahead, or that bicyclists may be present ahead. In general, accuracy was high and statistically equivalent for the 3 Foot Minimum and Share the Road signs.

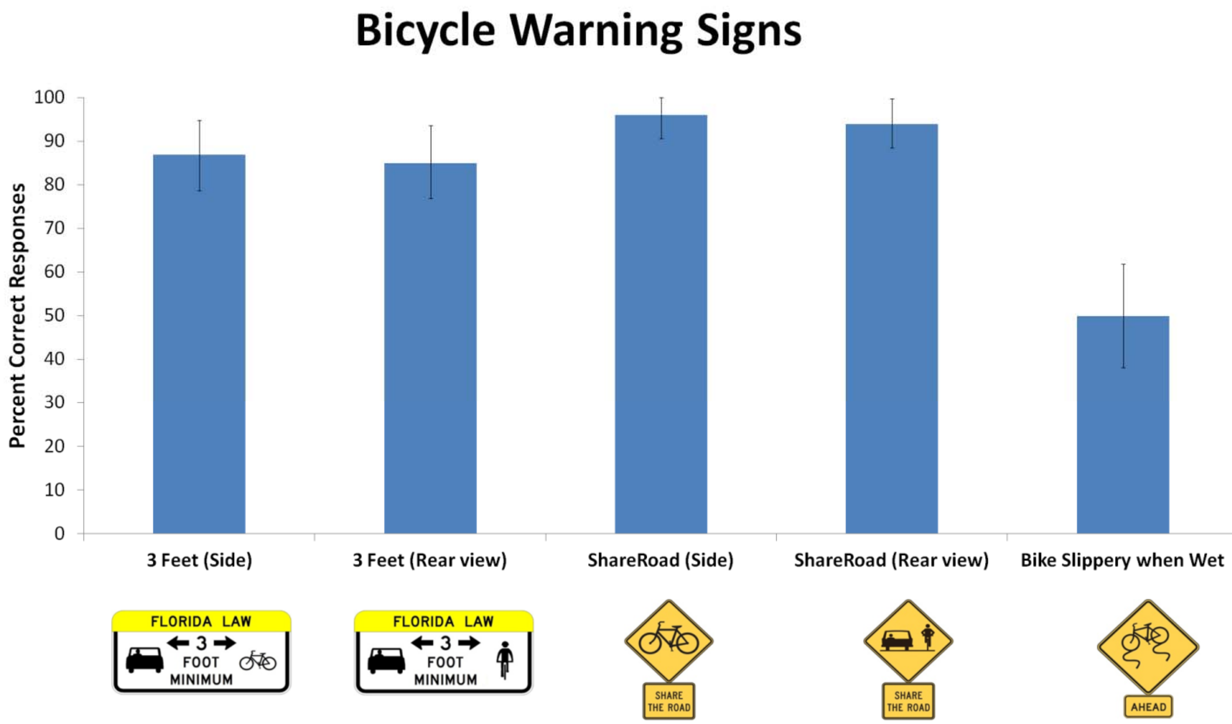

Figure 3. Sign knowledge accuracy (% of participants who correctly identified each sign) for all bicycle warning signs. Error bars represent 95% confidence intervals.

As indicated by Table 2, there was also a group effect for the bicycle Slippery when Wet sign. Younger adults were more likely to misinterpret the meaning of this sign (only 22% of young adults identified the meaning of this sign correctly). Middle-aged and older adults, in addition to cyclists, were more accurate (67, 56, and 59%, respectively).

Next we analyzed knowledge of various stop and yield signs related to pedestrian and bicyclist crossings. These data are depicted in Figure 4. Accuracy was generally high (>80% correct), and did not differ significantly as a function of sign type ($X^2(7, N = 272) = 12.70, p = .08$). As noted from Table 2, there were no significant differences as a function of age or bicyclist status (bicyclist vs. non-bicyclist).

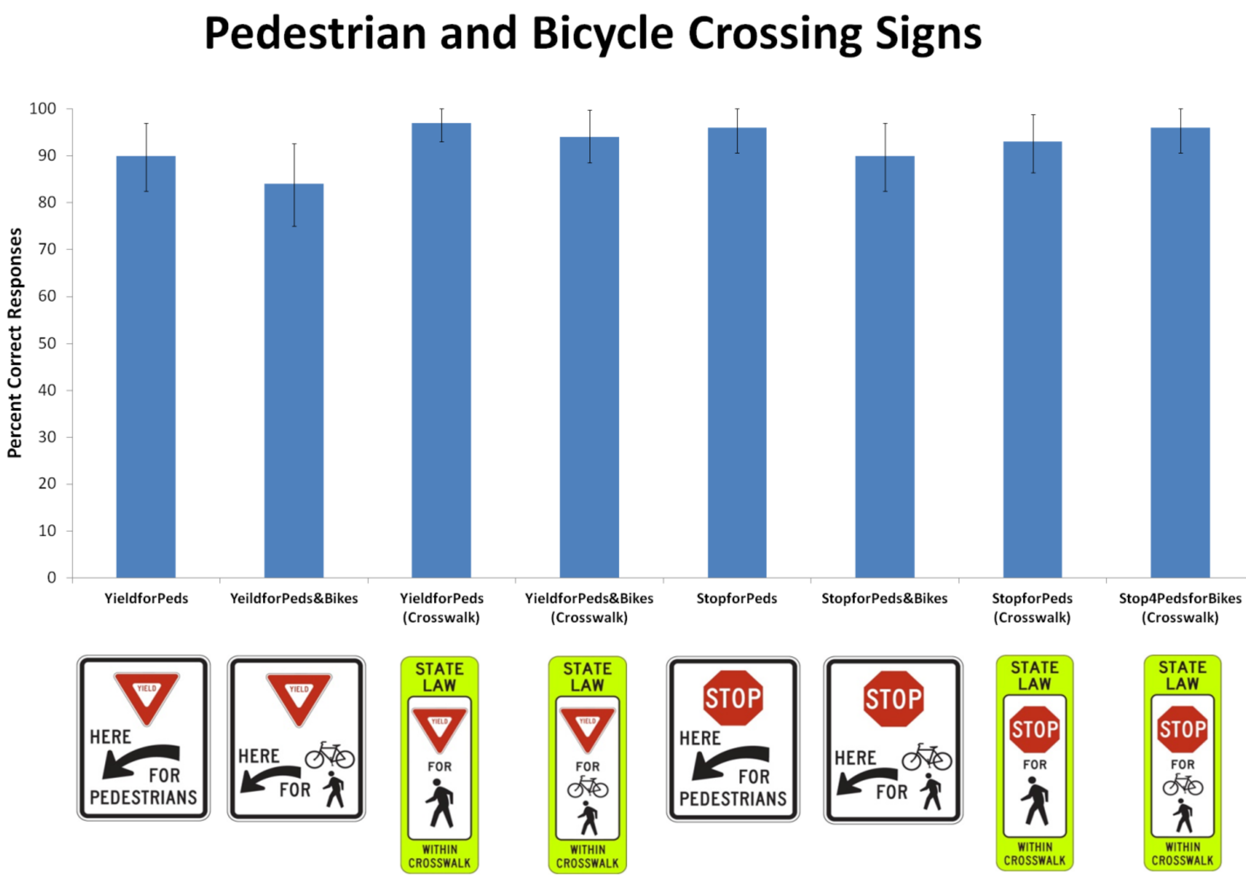

Figure 4. Sign knowledge accuracy (% of participants who correctly identified each sign) for all pedestrian and bicycle crossing signs. Error bars represent 95% confidence intervals.

Finally, we analyzed knowledge with respect to bicycle pavement markings. Figure 5 depicts accuracy for each marking. There was a significant difference between knowledge of markings ($X^2(3, N = 272) = 171.04, p<.001$), driven by poor performance in the Shared Lane or "Sharrow" condition and the complete lack of accurate responding in the Bicycle Detector pavement marking condition. The Bicycle Detector marking indicates where a bicyclist should position themselves in order for a traffic signal to detect their presence. Participants often interpreted the Sharrow as warning of an upcoming bicyclist crossing or an upcoming bike lane. Many participants understood that the marking indicated the direction bicyclists should travel, but did not report other important aspects of the marking's meaning (such as bikes can use this lane and that a motorist can expect to encounter cyclists in this lane position). For the Bicycle Detector, many participants explicitly mentioned never having seen this marking, and many were not willing to guess its meaning. This marking was also mistaken for a bike lane pavement marking. One factor that could have contributed to poor performance for some signs, such as the bicycle version of Slippery when Wet, and pavement markings, such as the Bicycle Detector marking, is the fact that they are infrequently or never used in the Tallahassee area (though participants may have encountered these elsewhere). As a result, participants would have rarely, if ever, encountered those signs/pavement markings and so would not have had the opportunity to learn their correct meaning.

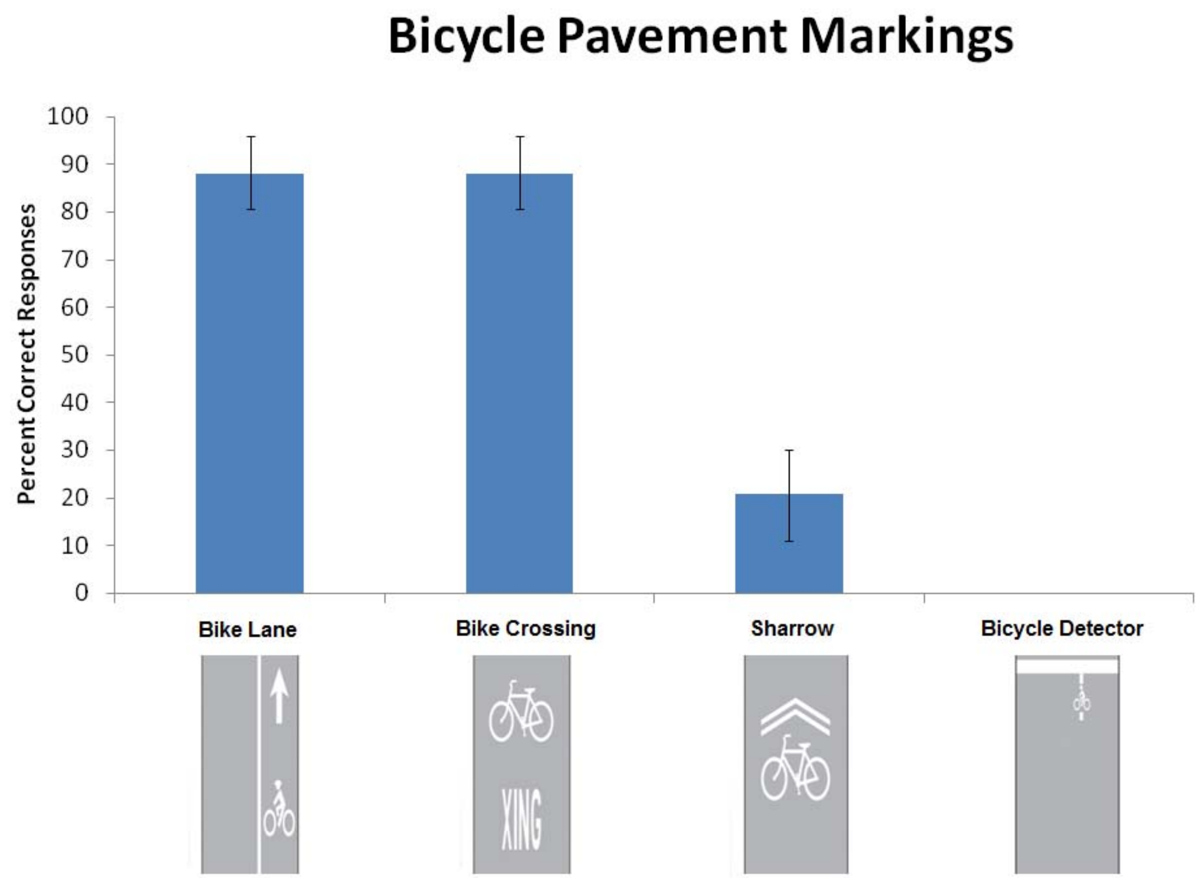

Figure 5. Pavement marking knowledge accuracy (% of participants who correctly identified each marking) for all bicyclist related roadway markings.

In general, all groups displayed fairly accurate knowledge of signs and pavement markings with some notable exceptions. The bicyclist Slippery when Wet sign was often misunderstood, especially among younger participants. The Sharrow and Bicycle Detector pavement markings were especially poorly understood, even by bicyclists, but this may be in part due to the lack of additional context involved in the sign knowledge task. A more realistic depiction of the Sharrow involving more roadway context might help drivers correctly interpret its meaning. Additionally, the Bicycle Detector marking is frequently paired with a sign explaining its meaning. Educational campaigns to help clarify the meaning of signs and pavement markings might improve both bicyclist and driver understanding of frequently misinterpreted signs and markings.

Speeded Comprehension

Of primary interest is the effectiveness of different signs at quickly and accurately conveying to drivers both the presence of bicyclists and the message that motorists must share the road with bicyclists. We examined whether the two versions of the 3 Foot Minimum sign and the two versions of the Share the Road sign differed in terms of how quickly and accurately participants could discern their message. The primary difference between these two sign versions was the profile of the bicycle/bicyclist. One version depicted a side view profile of a bicycle. The second version depicted a bicyclist's profile as one would see if the bicyclist were riding away from the viewer (refer back to Figure 1). See the Appendix for accuracy and response times for other signs and pavement markings.

A limitation of the speeded comprehension task was that, due to time constraints, only one trial contributed to each participant's response time measure for each sign at each distance. This was necessary to collect data from all thirteen signs at different simulated distances within the time allocated for the experimental sessions. Half of all trials were "foil" trials, that is, the initial text message presented (e.g., "Use caution. Cyclists may be present") did not match the meaning of the subsequent sign (e.g., a golf cart warning sign). On these trials, the ease of comprehending the foil sign also contributes to response time and accuracy. In the subsequent analyses, we focus on non-foil trials with the purpose of answering the question of how quickly and accurately participants can recognize the meaning of the subsequent sign of interest. Despite the limitations, consistent and clear patterns of results were observed.

Share the Road

Collapsed across all ages, and for both bicyclists and non-bicyclists, average response times for correct responses are depicted in Figure 6. Figure 7 depicts average accuracy collapsed across groups. Given that there was only one non-foil trial for each sign at each distance, it was possible for a participant to have no correct response times for a specific condition. This precluded an overall Analysis of Variance (ANOVA) approach; an overall within-participant ANOVA drops a participant out of the analysis if any condition is missing data for that participant, which would have resulted in few participants in the final analysis. Instead, a repeated-measures ANOVA was performed *for each distance* between each version of the Share the Road sign to maximize the number of included data points.

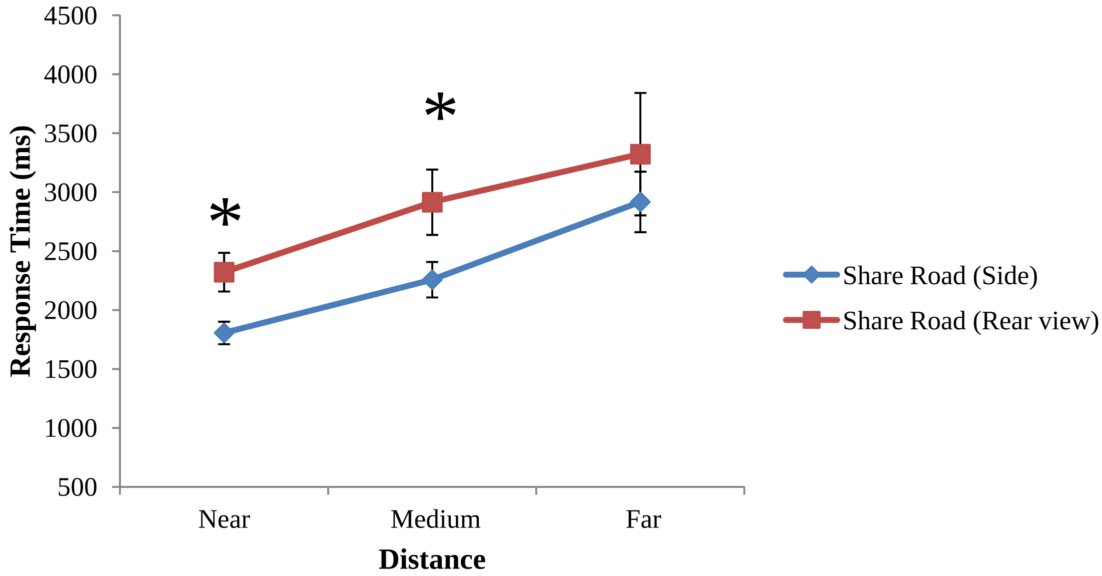

*Figure 6. Overall response time as a function of distance and Share the Road sign type. Error bars represent +/- 1SEM (standard error of the mean). * = p < .05.*

For the Share the Road Sign, robust and clear advantages of 515 ms and 657 ms were observed for the two nearest distances for signs featuring the sideways profile of a bicycle (20 and 198 feet). A repeated measures ANOVA at the near distance (20 feet), with Group (Younger, Middle, Older, Bicyclist) as a between factor subject revealed a significant response time advantage for the "side view" version of the Share the Road sign ($F(1, 45) = 5.30$, $p < .05$, $\eta_p^2 = .11$). Group did not interact with sign type, suggesting an equivalent advantage for each age group, and for bicyclist and non-bicyclist groups ($F(3, 45) = .75$, $p = .53$, $\eta_p^2 = .05$). Similarly, a repeated measures ANOVA at the medium distance (198 feet) revealed a significant response time advantage for the side view version of the Share the Road sign ($F(1, 42) = 12.68$, $p < .01$, $\eta_p^2 = .23$). Group did not interact with sign type, suggesting an equivalent advantage at this distance as well for each age group, and for bicyclist and non-bicyclist groups ($F(3, 42) = 2.56$, $p = .07$, $\eta_p^2 = .15$).

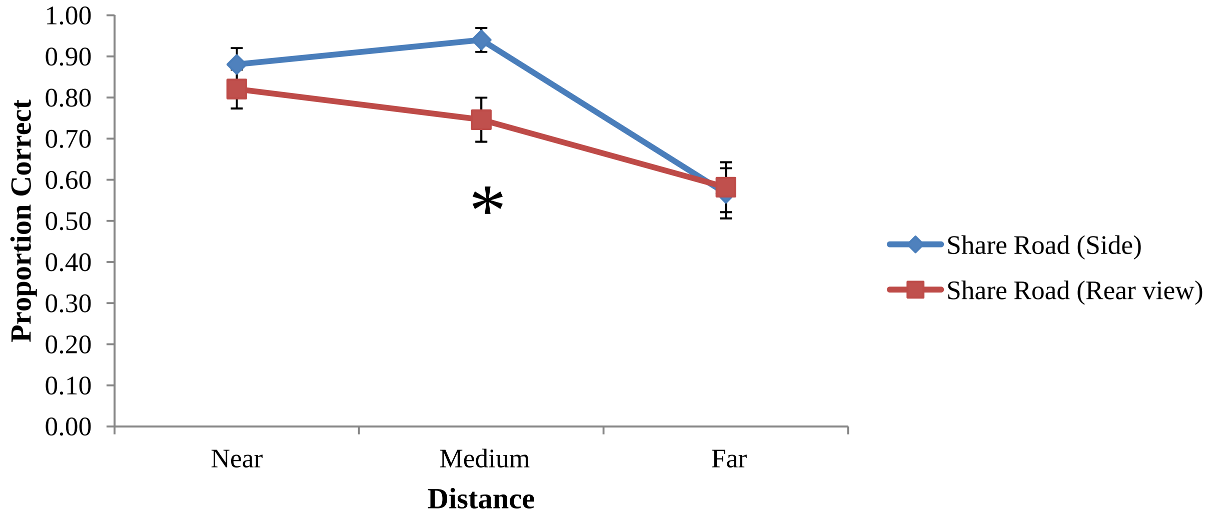

*Figure 7. Overall accuracy as a function of distance and Share the Road sign type. Error bars represent +/- 1SEM (standard error of the mean). * = p < .05.*

Next, we analyzed the data for accuracy of identification of the Share the Road sign. Since the speeded comprehension task featured only one trial at each distance, non-parametric statistics were used. Across all age groups and cycling status, participants tended to be more accurate at identifying the Share the Road sign featuring the sideways profile of the bicycle. There was a significant advantage at the middle distance for the side-view version of the sign ($X^2(2, N = 134) = 9.54, p<.01$). Data broken down by age group and bicyclist status did not reveal systematic differences other than older adults performing more poorly (especially at far distances).

Next we turn our attention to the two 3 Foot Minimum signs. Again, one featured the view of a bicyclist and bicycle as if the bicyclist were riding away from the viewer and the other displayed just the sideways view of a bicycle.

3 Foot Minimum

Average response times for correct responses are depicted in Figure 8. Accuracy is depicted in Figure 9. As for the Share the Road signs, there is evidence that the sign featuring the sideways profile of the bicycle was more rapidly understood, at least for the nearest distance.

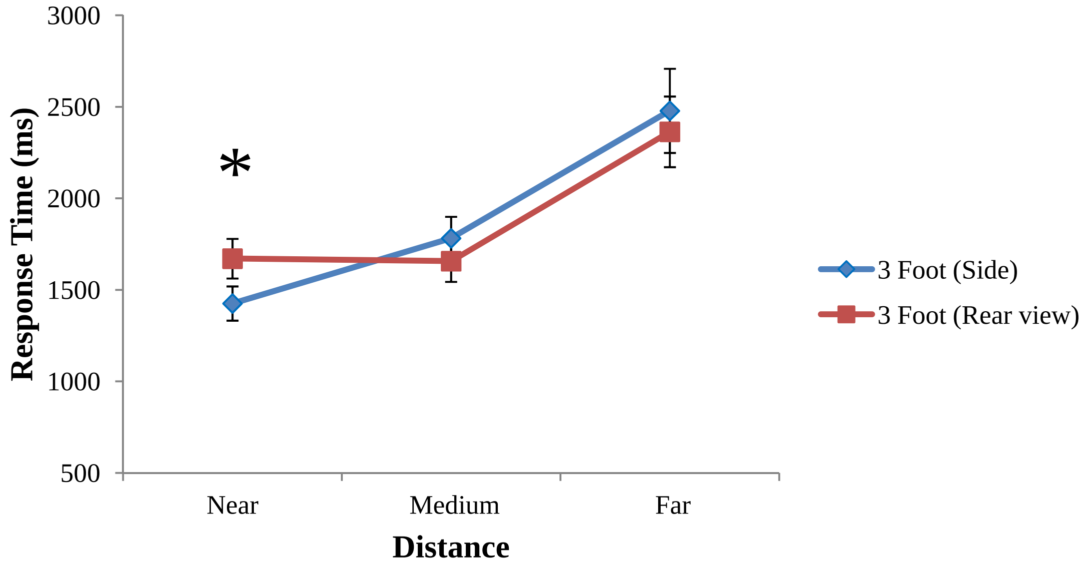

*Figure 8. Overall response time as a function of distance and 3 Foot Minimum sign type. Error bars represent +/- 1SEM (standard error of the mean). * = p < .05.*

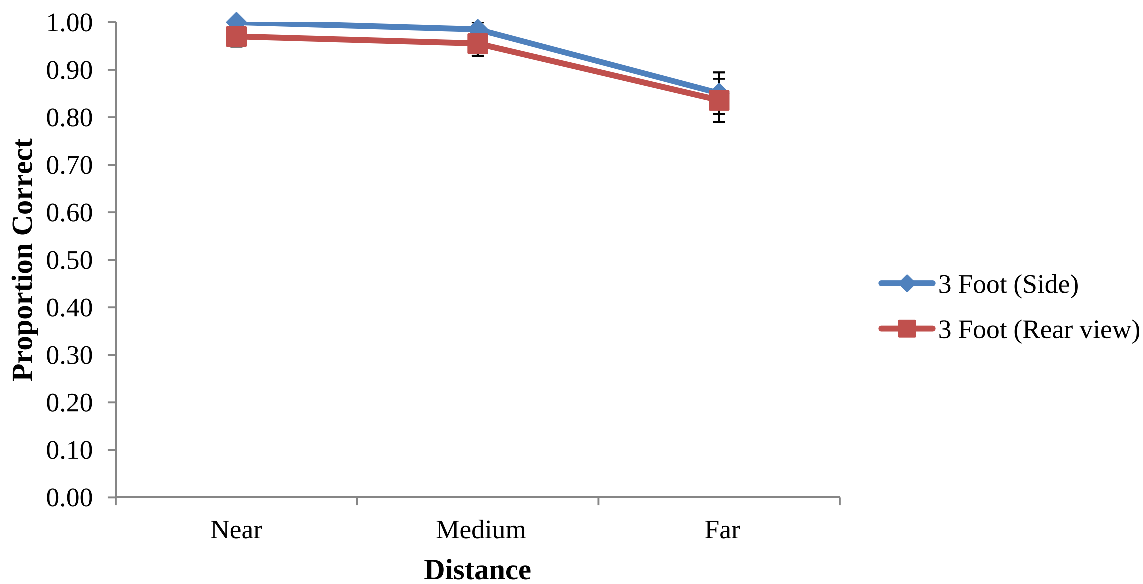

*Figure 9. Overall accuracy as a function of distance and 3 Foot Minimum sign type. Error bars represent +/- 1SEM (standard error of the mean). * = p < .05.*

Similar to the Share the Road signs, the 3 Foot Minimum sign featuring the sideway profile of a bicyclist was recognized more quickly, at least at the nearest distance ($F(1, 64) = 5.32$, $p < .05$, $\eta_p^2 = .08$). This was an advantage of about 245ms. Group did not interact with sign type, suggesting an equivalent advantage for each age group, and for bicyclist and non-bicyclist groups ($F(3, 45) = .75$, $p = .53$, $\eta_p^2 = .05$). A significant difference between the two versions of the sign was not observed at the further distances.

As for accuracy, there was no consistent pattern other than that of decreased accuracy with increased sign distance (aggregate data are depicted in Figure 9). Similar to the sign knowledge data reported above, both signs appeared to be very effective in conveying the intended message.

Comparing Share the Road and 3 Foot Minimum Signs

In terms of speeded comprehension, in both sets of signs the sign featuring a sideways profile of a bicyclist was comprehended more easily. We next evaluated the two signs featuring a sideways profile of a bicyclist to determine which is most quickly and accurately comprehended. Because of the size and shape of the signs, the 3 Foot Minimum and Share the Road signs could only be presented at 2 distances that were comparable between conditions (20ft, 198ft). There was a 380ms advantage for the 3 Foot Minimum (Side) compared to the Share the Road (Side) sign in terms of response time, and a 12% benefit in terms of accuracy for the nearest (20ft) distance ($X^2(1, N = 134) = 8.51, p<.01$). All other comparisons were non-significant.

Speeded Pattern Matching

We also explored whether the two versions of the 3 Foot Minimum sign and the two versions of the Share the Road sign differed in terms of how quickly and accurately participants could perceive them in a pattern matching task. Participants saw a sign at the near distance, and then after a delay saw either the same sign or a different sign at a near, intermediate, or far distance. For the pattern matching task, the critical measure was how quickly and accurately participants could judge (yes/no) that the identity of the second sign was the same as the first. This provides a measure of the perceptibility of the sign at different distances.

Share the Road

Average response times for correct responses are depicted in Figure 10.

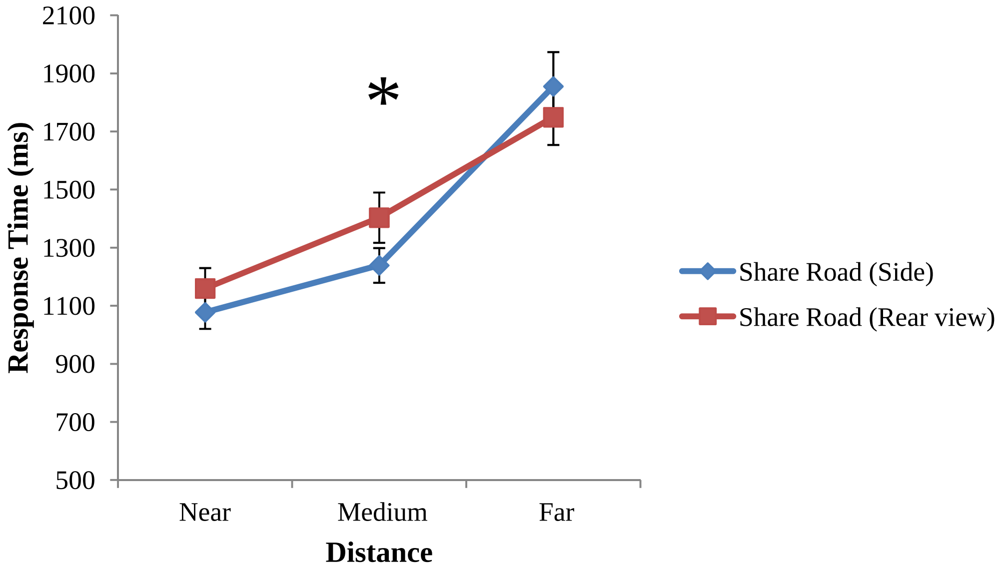

*Figure 10. Overall response time as a function of distance and Share the Road sign type. Error bars represent +/- 1SEM (standard error of the mean). * = p < .05.*

Given the greater number of trials and fewer missing data points, an overall within-participant ANOVA was performed with distance (near, medium, far), and sign (Side, Rear view) as within participant factors, and with Group (Younger, Middle, Older, Bicyclist) as a between participant factor. This revealed a complex 3-way interaction ($F(6, 110) = 2.62$, $p < .05$, $\eta_p^2 = .13$). Figure 11 appears to reveal the source of this interaction. Generally, there was an advantage for the side view sign, but this was most evident (in terms of size and consistency of the pattern) in bicyclist and younger participants, with a smaller advantage for middle-aged and older participants. At the very furthest distance, just for older participants, the pattern reversed such that there was a significant advantage for the rear-view bicycle Share the Road sign.

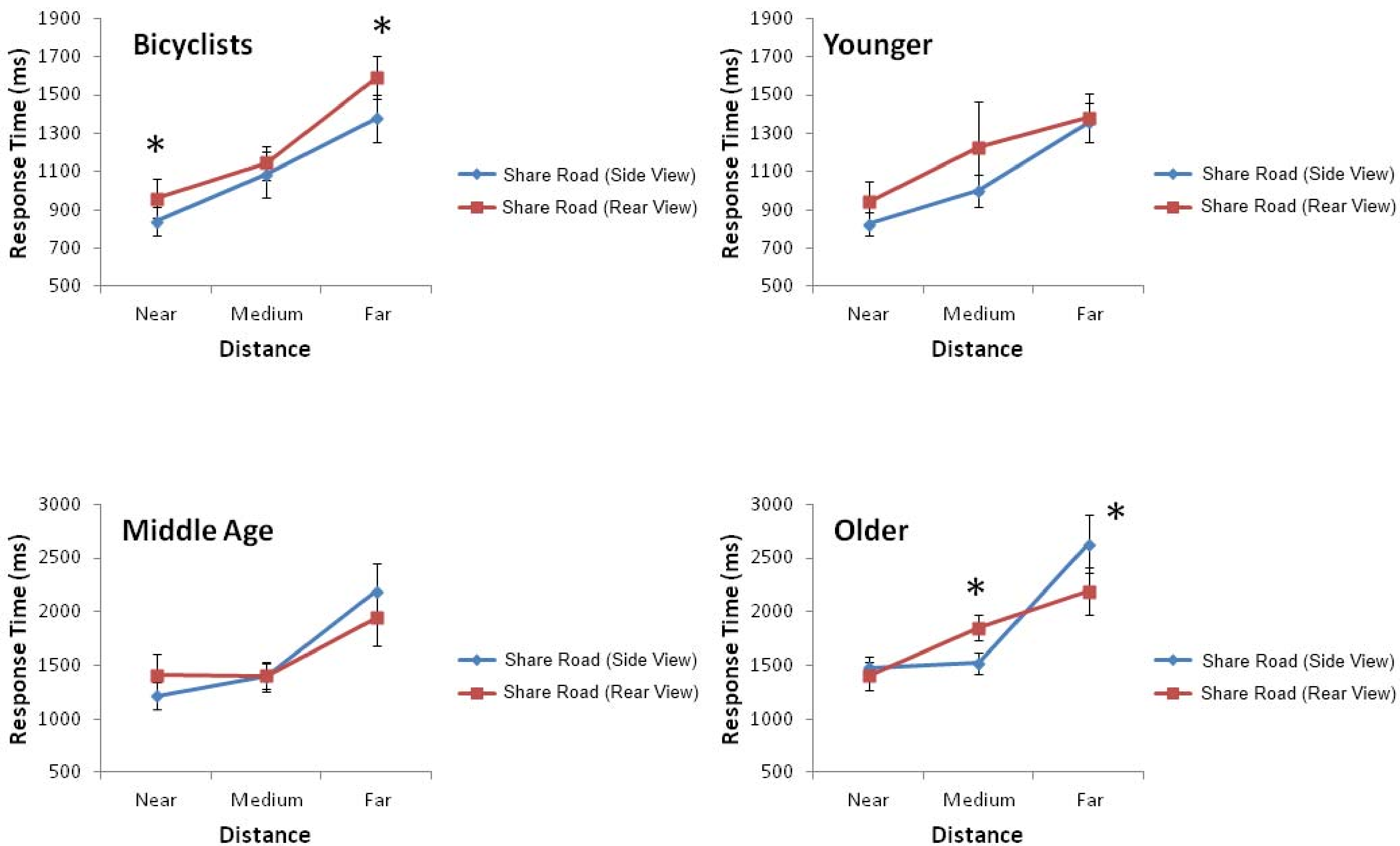

*Figure 11. Overall accuracy as a function of distance, group and sign type for the two versions of the Share the Road sign. The top left panel represents data from bicyclist participants, and the other three panels represent data from non-bicyclist younger, middle-aged, and older adults. Error bars represent +/- 1SEM (standard error of the mean). * = p < .05.*

An identical analysis was performed on accuracy (Figure 12). There was no overall effect of sign type($F(1, 55) = .36$, p=.55, $\eta_p^2 = .006$), and sign type did not interact with any other variable (all p values > .10).

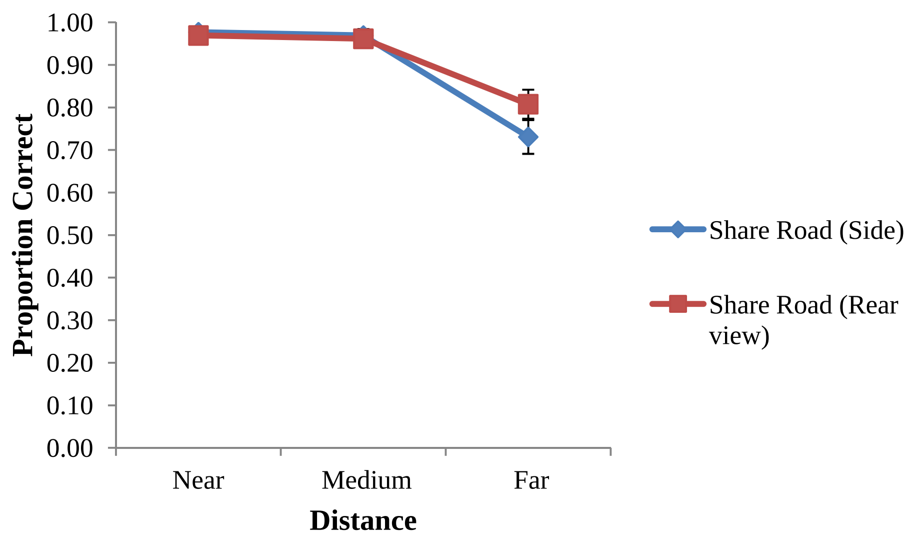

*Figure 12. Overall accuracy as a function of distance and Share the Road sign type. Error bars represent +/- 1SEM (standard error of the mean). * = p < .05.*

3 Foot Minimum

For the 3 Foot Minimum signs, average response times for correct responses in the pattern matching task are depicted in Figure 13. Accuracy is depicted in Figure 14.

An overall within-participant ANOVA was performed with distance (near, medium, far), and sign (Side, Rear view) as within participant factors, and with Group (Younger, Middle, Older, Bicyclist) as a between participant factor. This revealed an overall advantage for the rear view version of the 3 Foot Minimum sign ($F(1, 54) = 7.48$, $p < .05$, $\eta_p^2 = .12$). This advantage did not interact with group, suggesting an equivalent pattern for all ages and for cyclists and non-cyclists ($F(3, 54) = 1.43$, p=.24, $\eta_p^2 = .07$). This one finding appears anomalous in the context of the majority results suggesting a side-view advantage. This rear view advantage appeared to be true largely for the largest distance condition, as evidenced by the sign by distance interaction ($F(2, 114) = 3.70$, $p<.05$, $\eta_p^2 = .06$).

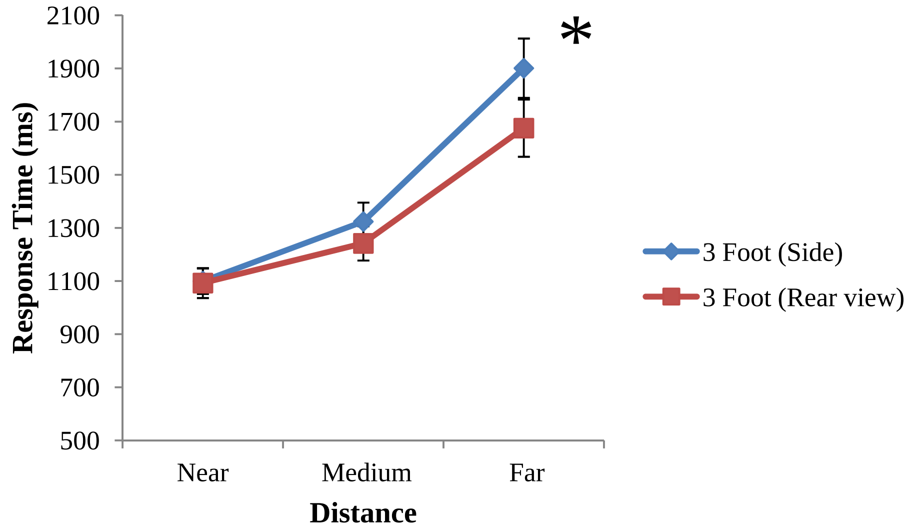

Figure 13. Overall response time as a function of distance and 3 Foot Minimum sign type. Error bars represent +/- 1SEM (standard error of the mean). * = p < .05.

An identical analysis was performed on accuracy (Figure 14), and while there was no overall effect of sign type ($F(1, 54) = 3.16$, p=.08, $\eta_p^2 = .05$), there was a trend at the greatest distance for accuracy to be higher for the rear view compared to the side view bicycle warning sign (sign x distance interaction: $F(3, 54) = 2.74$, p=.07, $\eta_p^2 = .05$). This effect was relatively weak compared to the response time advantage, and non-significant. All other interactions with sign type were non-significant (p > .11).

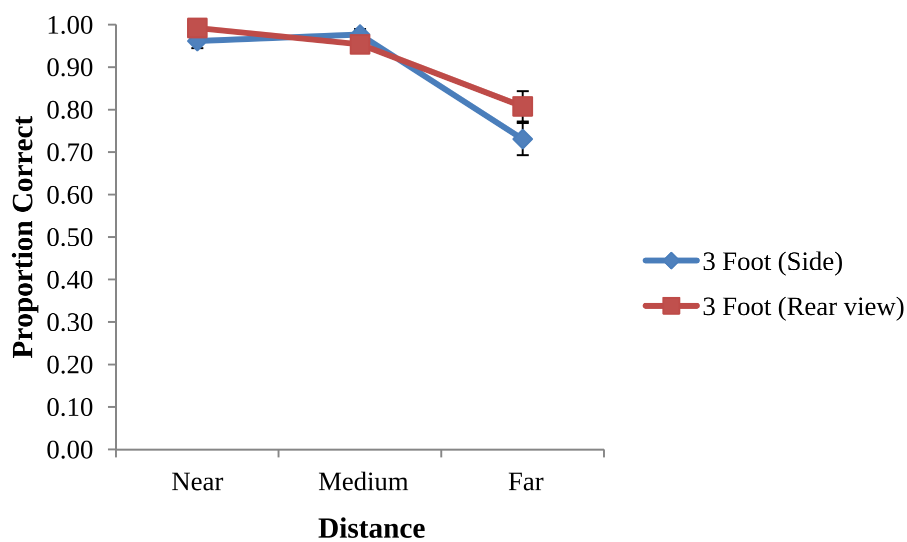

*Figure 14. Overall accuracy as a function of distance and 3 Foot Minimum sign type. Error bars represent +/- 1SEM (standard error of the mean). * = p < .05.*

Assessing Legibility after Blur

Schieber suggests blur tolerance methods as a way to predict sign legibility at a distance (McCall & Schieber, 2010; Schieber, 1994). Signs that depend on high spatial frequency contours to convey their message are unlikely to be perceived rapidly and accurately at a distance. Similar to this approach, we applied an 18 pixel Gaussian blur to images of each version of the Share the Road and 3 Foot Minimum sign to remove high spatial frequency content (Figure 15). Note that no features suggesting a bicycle are visible for the rear view versions, but the wheels and shape of the sideways bicycle are easily perceived (especially for the Share the Road sign) after the image has been degraded. Sign blurring is consistent with behavioral evidence in favor of the sideways bicycle versions of each sign.

Figure 15. 3 Foot Minimum and Share the Road signs after high frequency content has been reduced.

Conclusions

In general, signs and pavement markings related to the presence of pedestrians and bicyclists were understood well by all age groups. There was confusion related to the Sharrow and Bicycle Detector pavement markings and the Slippery when Wet bicyclist sign. Without a supplemental sign, no participant, including our bicyclist participants, knew the meaning of the Bicycle Detector pavement marking, highlighting the importance of also posting the sign at locations where Bicycle Detectors have been installed. With a few exceptions, signs depicting a sideways profile of a bicycle were understood and perceived more quickly and accurately compared to signs featuring the bicyclist riding away from the viewer.

Chapter 3.

Task 2: Simulator assessment of driver behavior with bicycle warning signs.

Designated bike lanes have been found in several instances to reduce rather than increase the distance that drivers place between their vehicles and bicyclists (separation distance; Parkin and Meyers, 2010). However, there are reasons to believe the potential hazard of shorter separation distances may be offset by the advantages of providing motorists with an unambiguous boundary between themselves and bicyclists (Harkey et al., 1996; Love et al., 2012). Meanwhile, the effects of several other potentially consequential variables have not been examined. In this report, we consider the effect of the presence and absence of bike lanes on separation distances and motorist speed as well as the effects of number of bicyclists, the presence of an oncoming motor vehicle, and the type of sign used to signal motorists to the potential presence of cyclists.

Researchers have identified several variables that influence the separation distance between motorists and cyclists. An analysis of over 2000 video-recorded passes by Sando and Moses (2011) revealed that greater separation distances were associated with lower traffic density. Separation distances in that study also tended to be shorter when the adjacent motorist lane (i.e., the lane on the driver’s side of the vehicle) was narrower or contained another motor vehicle (see also Harkey et al., 1996, p. 12 and 14). In addition, both Sando and Moses (2011) and Walker (2007) found evidence that female bicyclists elicit greater separation distances than males.

Among the many potential sources of variation in separation distance, the presence of designated bike lanes has received the most attention. Perhaps contrary to intuition, there is evidence that these lanes do not increase separation distances, and may actually reduce the distance between motorists and bicyclists (Harkey et al., 1996; Owens, 2005; Parkin& Meyers, 2010). For example, a study by Parkin and Meyers (2010) suggests that explicit demarcation of bike lanes may actually desensitize drivers to their proximity to bicyclists. Data from a helmet-mounted camera revealed that drivers gave a bicyclist more clearance when there was no designated bike lane when traffic speed exceeded 40 mph. Parkin and Meyer’s finding did not hold at speeds of lower than 30 mph, suggesting that the tendency of bike lanes to decrease separation distance may be limited to higher speeds. However, it is also worth noting that it is difficult to make comparisons between the roads examined by Parkin and Meyers because they differed significantly in traffic density; the road with a speed limit of 30 mph also had the highest average daily traffic of any of the other roads observed. Another study by Harkey et al. (1996) found that the presence of bike lanes was associated with shorter separation distances regardless of speed, noting that “speed limit…was not found to be a significant factor with respect to separation distance between the motorist and bicyclist and percentage of encroachments” (p. 19).

The emergence of speed as a potential moderator of the effect of bike lanes on separation distance in Parkin and Meyers' (2010) study may reflect a more complex design involving multiple variables, which led to greater variability in separation distances than that observed in Harkey et al. (1996). For example, although separation distances for most conditions reported in both studies are in the five- to six-foot range, Parkin and Meyers (2010) observed mean separation distances at their 40 mph site of less than four feet for both stretches of road with a bike lane and those without a bike lane. Thus, the greater variability in separation distances observed by Parkin and Meyers (2010) may reflect peculiarities of their 40-mph site that are distinct from the variables included in their analysis.

Although unqualified pronouncements are premature at this point, a defensible tentative conclusion is that designated bike lanes tend to decrease separation distances by up to one-half foot (Harkey et al., 1996; Parkin and Meyers, 2010), as this is what has been reported in most studies we reviewed that compared passing distances between roads with and without bike lanes. However, there is at least some evidence that the presence of bike lanes may decrease the number of close passes, at least under some traffic conditions.

It is important to note that evidence that designated bike lanes reduce the distance motorists place between themselves and bicyclists is not synonymous with evidence that designated bike lanes increase the likelihood of collisions between motorists and bicyclists. To the contrary, evidence suggests that designated bike lanes may reduce the risk of collisions despite stimulating drivers to place shorter distances between their vehicles and bicyclists. Harkey et al. (1996) found that the tendency of motorists to encroach on bicyclists was significantly greater in the absence (22.3%) versus the presence (8.9%) of a designated bike lane, despite finding a smaller average separation distance between the bicyclist and motor vehicle during passes between roads with bike lanes (M = 5.93 ft, SE = .051) compared to those with wide curb lanes (M = 6.44ft, SE = .074) or paved shoulders (M = 6.19ft, SE = .054). Stronger support for the efficacy of designated cycling lanes is provided by a study designed to assess the compliance of motorists with the three-foot law enacted in fourteen states requiring motorists to place a minimum of three feet between their vehicles and bicyclists (Love et al., 2012). Remarkably, although videos of 586 passes revealed that separation distances of less than three feet were relatively common on roads *without* bike lane designations, separation distances of less than three feet were never observed (0 of 88 passes) in the presence of designated bike lanes.

The current study further examined how four factors influenced separation distances as younger, middle-aged, and older drivers passed simulated cyclists in a driving simulator. These factors were 1) Bicycle Warning Sign and Warning Sign Type, 2) Bike Lane Presence, 3) Size of Bicyclist Group (1 vs. 7), and finally, 4) Oncoming Traffic Presence.

Method

Participants

Participants included in reported analyses were 32 younger (*M* = 24 yrs, 16 females), 34 middle-aged (*M* = 57 yrs, 20 females), and 38 older (*M* = 71 yrs, 21 females) adults. Younger adults were recruited from the undergraduate participant pool at Florida State University and advertisements placed on campus, whereas middle-aged and older adults were recruited from the community via newspaper ads. In total, 123 participants were run. The data from 19 participants were not included in the reported analyses because of the following: equipment malfunction (*N*= 9), simulator sickness (*N*= 5), the disregard of instructions (*N*= 3), and experimenter error (*N*= 2).

Materials

Driving Simulator: A NADS MiniSim high-fidelity driving simulator developed by The National Advanced Driving Simulator at the University of Iowa (Iowa City, IA), was used for the study. The NADS MiniSim incorporates a dashboard with a virtual instrument cluster, steering wheel; accelerator and brake pedals; and three 42” plasma displays that gives the driver a 180° horizontal and 50° vertical field of view of the simulated environment. Each display has a resolution of 1360 x 768 pixels and a refresh rate of 60 Hz. Our driving simulator is integrated with an SMI eye tracker to monitor eye and head movements (http://www.smivision.com/en/gaze-and-eye-tracking-systems/products/iview-x-hed.html).

Figure 16. Participant in the driving simulator and wearing the eye tracker used in reported studies.

<u>Simulated Driving Task:</u> In this task, participants maneuvered a simulated vehicle along a rural two-lane road with the instruction not to exceed 50 miles per hour. On 14 occasions, an individual bicyclist (7 occasions) or group of bicyclists (7 occasions) appeared along the side of the road following the appearance of either one of three warning signs or no warning sign (see Figure 17), depending on the condition. In the sign conditions, one of three possible signs appeared. Thus, there were four conditions: the Share the Road sign condition, the 3 Foot Minimum sign condition with a rear view of a bicyclist, an alternative 3 Foot Minimum sign condition with a side view of a bicycle, and a condition with no sign. Individual bicyclists or groups of bicyclists appeared on the side of the road either in a bike lane or not in a bike lane (Figure 18a, Figure 18b; see Figure 2, left-most image for specific pavement marking placed within the bike lane). The distance of the bicyclist or bicyclist group from the edge of the road was identical in both lane conditions to isolate the effect of the presence of the bike lane, irrespective of bicyclist's distance from the motorist's vehicle. The four versions of the task were fully counterbalanced. Proximity of the vehicle to individual cyclists and groups of cyclists was recorded (see below for more detail about how proximity was calculated).

Share the Road (Side) | 3 Foot (Side) | 3 Foot (Rear view)

Figure 17. Sign set used in the simulated driving task.

Measure and Event Definitions

<u>Passing Event:</u> A passing event took place when a participant's vehicle got within a 50 ft range of a bicyclist or group of bicyclists on the axis parallel to the road. That is, a passing event started when the participant's vehicle was 50 ft behind a bicyclist and ended when the participant's vehicle was 50 ft ahead of a bicyclist.

<u>Separation Distance:</u> For individual bicyclists, separation distance was measured as the length between the participant's right side mirror and the end of the bicyclist's left handlebar. For bicyclist groups, separation distance was measured as the length between the participant's right side mirror and the end of the *left-most* bicyclist's left handlebar (also see Figure 19).

<u>Mean Passing Speed:</u> This is the participant's mean speed within a single passing event. Every participant will have a mean passing speed for each passing event.

<u>Minimum Separation Distance:</u> This is the participant's minimum separation distance within a single passing event. Every participant will have a minimum separation distance for each passing event.

<u>Age Group:</u> The age group the participant belonged to (Young, Middle, Old).

<u>Sign Condition:</u> The sign used in the scenario (see Figure 17).

<u>Oncoming Vehicle:</u> Whether or not a vehicle was passing in the oncoming lane while the participant approached the bicyclist or group of bicyclists.

<u>Bike Lane:</u> Whether or not the bicyclist or group of bicyclists was traveling in a bike lane when the participant passed.

<u>Bicycle Group Size</u>: The number of bicyclists the participant passed (1 or 7).

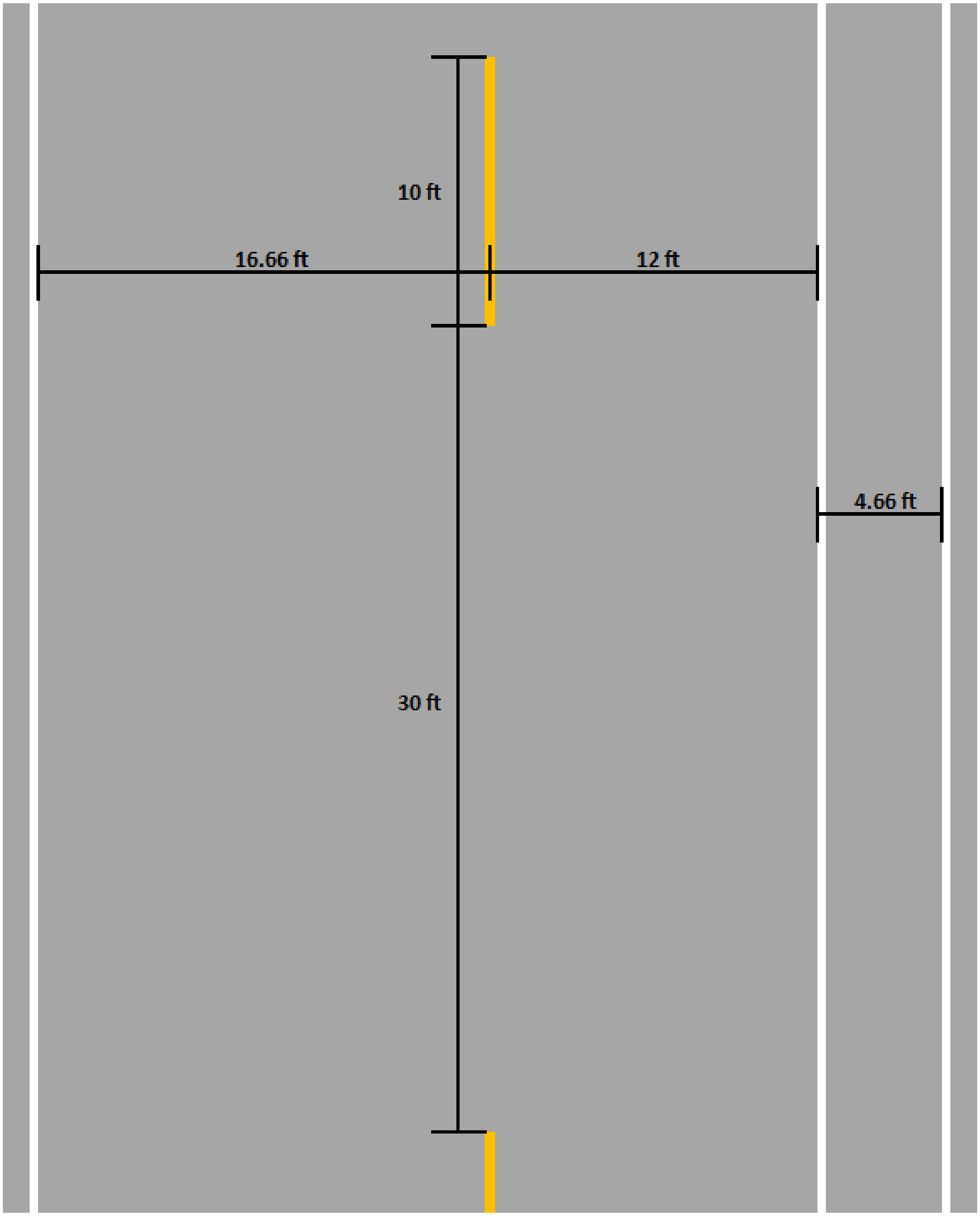

Figure 18. Condition with bike lane present (right side).

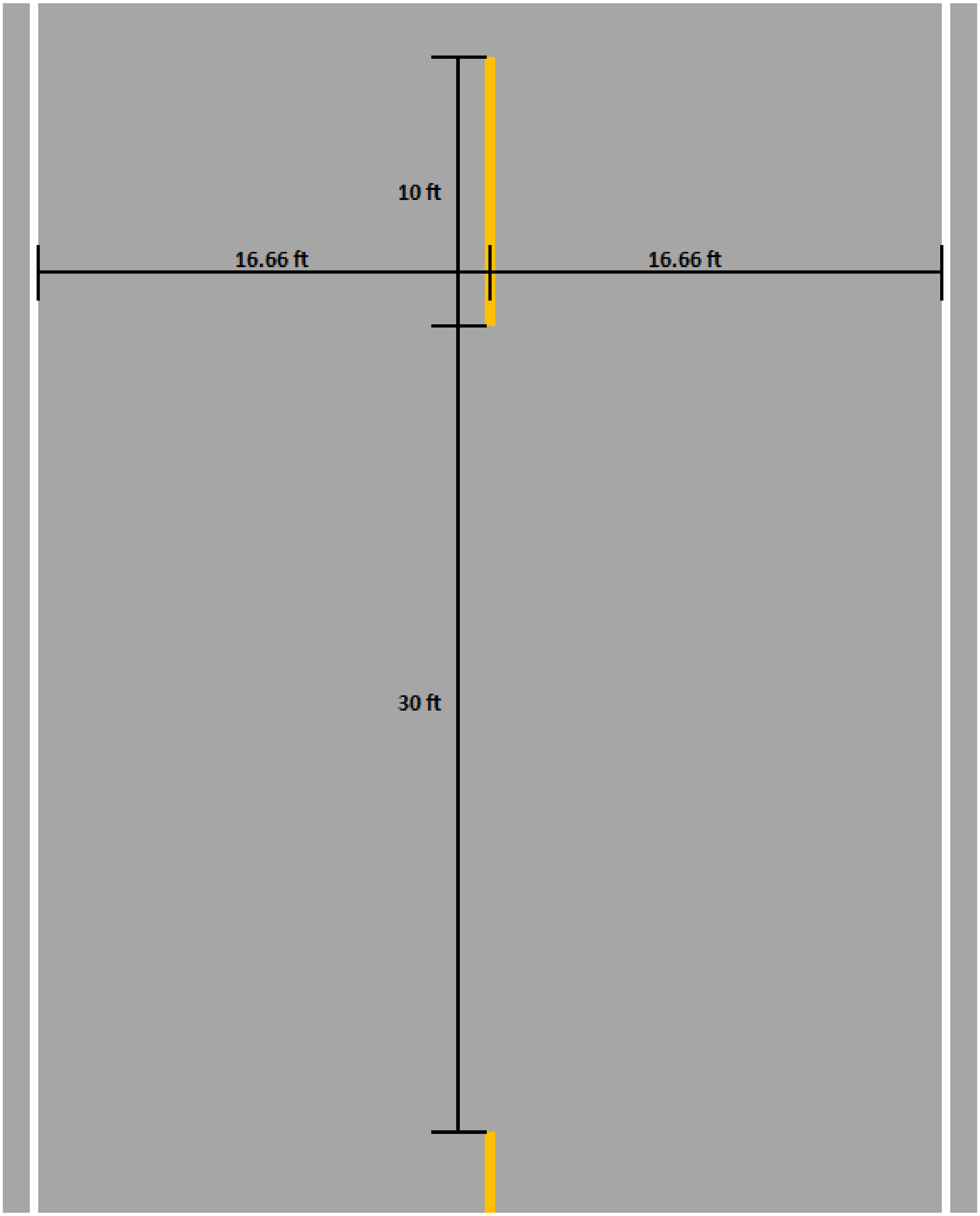

Figure 19. Condition with no bike lane present.

Note that the lane width of 16.6 here is larger than the typical 12 ft travel lane. This was done to equate the distance of the bicyclist in the bike lane present and absent conditions. A larger than typical lane width makes the bike lane absent condition more similar to a wide curb lane (Hunter et al., 1999; Sando & Moses; 2011).

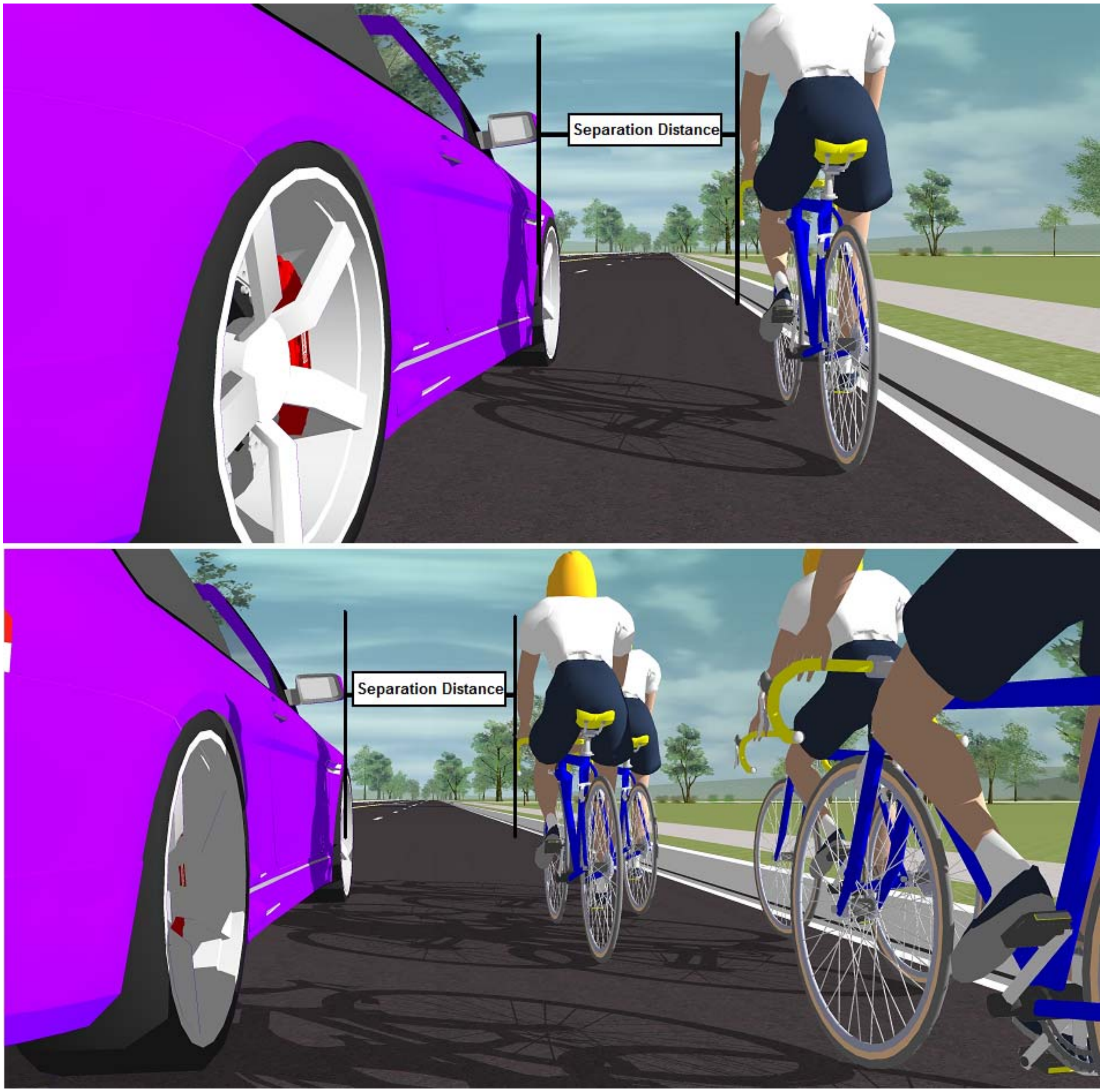

Figure 20. Illustration of how separation distance was measured for individual (top panel) and bicyclist groups (bottom panel). Note that this figure is meant to illustrate measurement procedures only and does not depict the actual driving scenario.

Analytic Technique

Multilevel linear modeling was used to examine bicycle separation distance and passing speed. By using multilevel modeling, we are able to examine these variables on a trial-level basis. That is, rather than aggregating separation distance and speed across conditions, we are able to retain every trial, and as a consequence, take into account the between-trial variation for these variables, thereby increasing the precision of our estimates and power in detecting an effect (Hox, 2010). We are also able to add both trial and individual-level predictors to the same model. In regular linear regression, doing this would violate assumptions of independence, however, with multilevel modeling we are able to treat intercepts and/or slopes as random effects, thereby allowing us to estimate and account for the variance associated with groups (e.g., participants; Tabachnick & Fidell, 2007).

Results

Summary statistics for minimum separation distance and mean passing speed are displayed in Table 3. Separation distances elicited in the simulator were comparable to those observed in other studies using different methods such as video recordings of actual traffic (e.g., Harkey et al., 1996; Parkin & Meyers, 2010). These previous studies report distances of roughly four to six and one-half feet, depending on moderators such as speed limits, presence of a bike lane, and type of motor vehicle (e.g., car versus truck).

All data were processed using Python version 2.7.3. and analyzed using R version 2.15.1. The R nlme library version 3.1-105 (Pinheiro et al., 2008) was used for multilevel modeling. Before conducting analyses, the distributions of the variables were checked. During this check, it was found that minimum separation distance was skewed in the positive direction, meaning that most values fell in the lower end of the range of possible values, and this was corrected using a square root transformation in order to make the data meet the assumption of normality. All following analyses that include minimum separation distance use this transformed variable.

Table 3. Summary statistics for separation distance and speed of each condition in the driving simulator task of Task 2.

Variable	Min. Separation Distance (ft)		Mean Separation Speed (mph)		
	M	Range	*M*	Range	*n*
Age Group (Between-S)					
Young	6.39	3.76 - 9.94	50.05	44.27 - 58.42	32
Middle	6.65	4.64 - 9.97	47.82	33.51 - 55.19	34
Old	6.24	4.24 - 13.50	46.48	35.88 - 57.33	38
Sign Cond. (Between-S)					
Share the Road	6.38	4.52 - 10.00	48.48	41.69 - 55.19	21
3ft Min. (Side)	6.39	4.24 - 9.04	48.41	33.51 - 58.43	28
3ft Min. (Rear)	6.68	5.05 - 9.94	47.57	37.81 - 57.33	28
No Sign	6.19	3.76 - 13.50	47.71	38.11 - 55.95	27
Oncoming Vehicle (Within-S)					
Present	4.74	2.52 - 6.70	45.90	29.04 - 59.61	54
Absent	6.16	4.42 - 10.44	48.99	33.81 - 58.40	
Bike Lane (Within-S)					
Present	6.23	3.38 - 13.65	48.91	31.39 - 58.68	104
Absent	6.60	3.17 - 13.35	47.14	35.64 - 59.47	
Bicyclist Group Size (Within-S)					
One	5.99	2.92 - 12.31	48.50	34.10 - 56.89	104
Seven	6.85	4.58 - 14.70	47.54	31.45 - 60.37	

Bicycle Separation Distance Model

A multilevel model using full maximum likelihood estimation was used to look at the influence of bike lane condition, bicyclist group size, oncoming vehicle condition, and bicycle warning sign condition on minimum bicycle separation distance. As can be seen in Equation 1, bike lane condition, bicyclist group size, and oncoming vehicle condition were added as level 1 variables as they varied within each participant; that is, each participant experienced every level of these variables (e.g., bike lane vs. no bike lane, bicyclist group vs. single bicyclist, etc.). Sign condition was added as the only level 2 variable as it only varied between participants; that is, participants only saw one type of sign condition. This specification resulted in the use of 104 participants who had a total of 1244 trials.

Level 1: $Y_{ti} = \beta_{0i} + \beta_{1i}\text{BikeLane}_{ti} + \beta_{2i}\text{GroupSize}_{ti} + \beta_{3i}\text{OncomingVehicle}_{ti} + \varepsilon_{ti}$

Level 2: $\beta_{0i} = \gamma_{00} + \gamma_{01}\text{SignCondition} + u_{0\text{i}}$

Before specifying the full model as shown above, three smaller, less complex models were calculated in order to determine whether or not the full model was necessary for explaining the data or if one of the less complex models was sufficient for this task. The first model specified was a base, intercept-only model whose only predictor was the intercept (in this case, the intercept was the mean of the minimum separation distance data).

This initial model was then compared using a likelihood ratio test to a second, random intercept-only model in which the intercept was specified as being a random variable. This comparison was made in order to determine if participants varied enough between each other to warrant the use of a random intercept. Overall, this was the case, $X^2(1) = 322.67$, $p < .01$. The third model included all of the variables from the level 1 equation and was compared to the second and full model. Overall, these comparisons supported the retention of the third model, $X^2(3) = 162.01$, $p < .01$, but not the retention of the full model, $X^2(3) = 2.25$, $p = .52$. The last comparison indicates that the addition of the sign condition variable did not explain enough variance beyond that already explained by the third model (i.e., there was not a significant effect of sign condition). Equation 2 (below) displays the layout of the final model, which was the third model calculated above.

Level 1: $Y_{ti} = \beta_{0i} + \beta_{1i}\text{BikeLane}_{ti} + \beta_{2i}\text{GroupSize}_{ti} + \beta_{3i}\text{OncomingVehicle}_{ti} + \varepsilon_{ti}$

Level 2: $\beta_{0i} = \gamma_{00} + u_{0\text{i}}$

Within the final model, all of the predictors showed relationships to minimum separation distance that were significant at the .05 level. Participants tended to pass bicyclists 0.37 ft closer when a bike lane was present compared to when one was absent, and 1.42 ft closer when an oncoming vehicle was present compared to when one was absent. Finally, participants tended to pass bicyclists 0.86 ft further away when they were passing a group of seven bicyclists compared to when they were passing a single bicyclist.

Summaries of these relationships as well as of the full model are shown in Tables 4 and 5.

Table 4. Model comparison results for minimum separation distance.

Model	-2 Log Likelihood	df	X^2 Difference Test
First	1338.60	2	
Second	1015.94	3	322.66*
Final	853.93	6	162.01*
Full	851.67	9	2.25

* Significant at the .05 level.

Table 5. Summary statistics for the full and final models for minimum separation distance.

Variable	Parameter Estimate (sqrt)	*SE*	df	*t*	*p*
Final Model (τ^2 = 0.06, σ^2 = 0.10)					
Intercept	2.48	0.03	1137	87.35	< 0.01
Bike Lane	-0.09	0.02	1137	-4.95	< 0.01
Group Size	0.17	0.08	1137	9.74	< 0.01
Oncoming Vehicle	-0.29	0.04	1137	-7.78	< 0.01
Full Model					
Intercept	2.47	0.06	1137	43.44	< 0.01
Bike Lane	-0.09	0.02	1137	-4.94	< 0.01
Group Size	0.17	0.02	1137	9.73	< 0.01
Oncoming Vehicle	-0.29	0.04	1137	-7.75	< 0.01
Share the Road vs. No Sign	0.06	0.07	100	0.80	0.43
3ft (Side) vs. No Sign	0.00	0.07	100	0.03	0.98
3ft (Rear) vs. No Sign	-0.04	0.07	100	-0.60	0.55

Bicycle Passing Speed Model

The same models and model comparison procedures used above were used to assess mean bicycle passing speed. Table 6 displays the summaries of the models and Table

7 displays the results of the model comparisons. As can be seen in Table 6, the second and third (final) models explained a sufficient amount of variance beyond that which was already explained by the models before them. The full model, the one that included the sign condition variable, however, did not explain enough variance beyond that which was already explained by the third model, therefore, the third model was retained as the final model. Again, for the final model, all predictors were significant at the .05 level. Participants tended to pass bicyclists 0.96 mph slower when passing a group of seven cyclists compared to when passing a single bicyclist, and 2.58 mph slower when an oncoming vehicle was present compared to when one was absent. Finally, participants tended to pass bicyclists 1.77 mph faster when a bike lane was present compared to when one was absent.

Table 6. Model comparison results for mean passing speed.

Model	-2 Log Likelihood	df	X^2 Difference Test
First	8489.02	2	
Second	8218.59	3	270.44*
Final	8167.86	6	50.73*
Full	8166.98	9	0.87

* Significant at the .05 level.

Table 7. Summary statistics for the full and final models for mean passing speed.

Variable	Parameter Estimate (sqrt)	*SE*	df	*t*	*p*
Final Model (τ^2 = 0.06, σ^2 = 0.10)					
Intercept	47.92	0.51	1137	94.80	< 0.01
Bike Lane	1.55	0.34	1137	4.45	< 0.01
Group Size	-0.97	0.34	1137	-2.86	< 0.01
Oncoming Vehicle	-2.93	0.72	1137	-4.08	< 0.01
Full Model					
Intercept	48.41	1.00	1137	48.13	< 0.01
Bike Lane	1.55	0.34	1137	4.53	< 0.01
Group Size	-0.97	0.34	1137	-2.85	< 0.01
Oncoming Vehicle	-2.93	0.72	1137	-4.08	< 0.01
Share the Road vs. No Sign	-0.99	1.29	100	-0.77	0.45
3ft (Side) vs. No Sign	-0.13	1.29	100	-0.10	0.92
3ft (Rear) vs. No Sign	-0.75	1.30	100	-0.57	0.57

Assessment of Sign Type Differences as a Function of Sign Fixation

We also assessed possible differences in minimum separation distance and mean passing speed between the signs when only including those participants who actually gazed-upon one of the three signs present in the scenario. We did this as we would expect participants to follow a sign's instructions only when they have read the sign. Table 8 displays the summary statistics for the sign conditions as a function of sign fixation.

The level 1 and full models for both minimum separation distance and mean passing speed as detailed above were rerun with only those participants who had fixated on the signs. For each outcome variable, the two models were compared using a likelihood ratio test. Overall, for both separation distance and speed model comparisons, model fit did not improve with the full model, whose only modification was the addition of the sign condition variable: $X^2(3) = 0.79$, $p = 0.85$ for the level 1 and full model comparison for minimum separation distance and $X^2(3) = 1.23$, $p = 0.74$ for the level 1 and full model comparison for mean separation distance. In addition, the revised parameter estimates for both models did not substantially differ from those generated from the previously detailed models.

Table 8. Summary statistics for sign conditions as a function of sign fixation.

Sign	Min. Passing Distance (ft)		Mean Passing Speed (mph)			
	M	*SD*	*M*	*SD*	*n*	% Within Sign Type
Participants with Eye Tracking Data*						
Share the Road	6.36	1.67	48.53	2.81	12	100%
3ft Min. (Side)	6.27	1.13	49.31	6.16	15	100%
3ft Min. (Rear)	6.58	1.41	48.09	4.54	16	100%
No Sign	6.19	1.80	47.71	3.73	27	100%
Participants who Fixated						
Share the Road	6.35	1.84	48.43	3.08	10	83%
3ft Min. (Side)	6.35	1.14	49.34	6.39	14	93%
3ft Min. (Rear)	6.58	1.41	48.09	4.54	16	100%
Participants who did not Fixate						
Share the Road	6.42	0.59	49.00	0.68	2	17%
3ft Min. (Side)	5.21	N/A	48.91	N/A	1	7%
3ft Min. (Rear)	N/A	N/A	N/A	N/A	0	0%

* All participants in the No Sign condition were also used in this analysis regardless of whether or not they had eye tracking data available. For the other conditions, eye tracking data was required as without it, it would have been impossible to determine whether or not participants looked at the sign.

Supplemental Results for Task 2

In order to determine whether or not sign type/presence may have impacted the number of fixations made on the bicyclists, the number of fixations made on all cyclists were submitted to a simple one-way ANOVA using sign type (3 Foot Minimum – Rear view, 3 Foot Minimum - Side, Share the Road - Side, and no sign) as the sole between subjects factor. Overall, the main effect of sign type did not reach significance at the .05 level, $F(3, 53) = 1.14$, $p = .34$. That is, the type or presence of bicyclist signs did not lead to more attention toward bicyclists. In addition, no difference in the number of fixations made towards cyclists was found between scenarios that featured any sign type, and the scenario that featured no sign, $t(55) = .29$, $p = .77$, $d = .09$. However, the frequency of fixations on bicyclists was quite high, leaving little room to detect a significant difference.

Conclusions

Overall, it was found that the minimum separation distances given to bicyclists were greater when there was more than one bicyclist and when there was no designated bike lane or oncoming vehicle present. In addition, passing speed was greater when there was only one bicyclist, a bike lane was present, and there was no oncoming vehicle. The type of sign placed in the driving scenarios had no apparent impact on either separation distance or passing speed under the conditions studied.

Chapter 4.

Exploring the Perceptual and Decision-Making Processes Involved in Left-Turn Crashes (Task 3a) and Assessing the Factors that Contribute to Left-Turn Behavior (Task 3b).

Even though intersections account for a small proportion of the total roadway, approximately 43% of all traffic-related fatalities and serious injuries in Florida occur at intersections or are influenced by intersections (FDOT, 2006). Crashes in which left-turning vehicles are struck by oncoming traffic at signalized intersections (left-turn crashes) are both common and severe (Wang & Abdel-Aty, 2008; Yan et al., 2007). Generally, older adult drivers are at greater risk for intersection crashes (Preusser et al., 1998), and left-turn crashes are particularly dangerous for older adult drivers relative to younger drivers (ADOT, 1996; Alexander et al., 2002).

A critical aspect of left turn decisions is the determination of whether there is a sufficient gap in space and time that would allow a driver to safely navigate through oncoming traffic in the lanes to the left of the driver. One major challenge to understanding the difficulty faced by older adults in making gap-acceptance judgments is that there is not yet an accepted general model of how judgments are made to serve as a framework for making predictions about how age should affect judgments. It is unclear, for example, even whether drivers merely judge the distance and speed of oncoming vehicles or actually attempt to estimate their arrival time (Davis & Swenson, 2004). Moreover, the weight given to various decision criteria appears to be influenced by complex, top-down cognitive factors such as whether drivers face time constraints (Lobjois & Cavallo, 2007).

Despite this uncertainty, a model by Davis and Swenson (2004) reveals the best predictor of gap acceptance to be simply the distance of oncoming vehicles, with the speed and time of arrival making weaker contributions. A troubling consequence of the same finding is that the likelihood of drivers accepting a gap of a given duration increases as the speed of the approaching vehicle increases. For example, a gap of five seconds is more likely to be accepted if the oncoming vehicle is traveling at 60 miles per hour than if it is traveling at 40 miles per hour. It appears that heavy reliance on distance as a cue creates a hazardous scenario whereby misjudgments are most likely to occur under the very conditions that will result in the most severe collisions. This same finding has been observed across age groups (Lobjois & Cavallo, 2007). There is at least some evidence that older adults are especially insensitive to the speed of oncoming traffic, relying even more on distance as a cue (Staplin, 1995).

One relatively robust finding to emerge from age group comparisons is that older adults accept longer gap durations than middle-aged adults or younger adults. The difference in gap durations accepted by older adults appears to be about one-half to a full second greater than the duration accepted by younger adults (Dissanayake, Lu, & Yi, 2002;

Lobjois, & Cavallo, 2007; Skaar, Rizzo, & Stierman, 2003; Yan, Radwan, & Guo, 2007). The longer gap durations accepted by older adults appear to be, at least in part, a means of coping for the lower acceleration and speed with which they typically maneuver (Skaar et al., 2003), as well as perceptual and cognitive declines that accompany the aging process, which in turn impair the ability of older drivers to correctly judge the speed/distance of oncoming vehicles and the gaps between vehicles (Scialfa et al., 1991; Stamatiadis et al., 1991). Despite this compensation, however, older adults are still at differential risk.

Situational factors may relate to this differential risk. There is some evidence that older adult gap-acceptance judgments are impaired more than those of younger adults when having to respond to a verbal message during a left turn (Cooper & Zheng, 2002). Moreover, in contrast to younger adults whose judgments did not change under time constraints relative to no time constraints, older adults were willing to accept shorter gap durations under time constraints. This suggests older adults may be more susceptible to collisions with oncoming vehicles when they feel compelled to make decisions quickly because of personal deadlines or perceived pressure from other drivers (Lobjois & Cavallo, 2007).

A proposed solution to the problem of left-turn crashes is greater offset of the left-turn lane of oncoming traffic to the right, allowing a view of oncoming traffic that is unobstructed or less obstructed by vehicles in the opposite left-turn lane. There are several ways in which left-turn lanes can be configured, resulting in lesser or greater offset. Figure 20 illustrates the difference between a negative offset and a positive offset. A left-turn lane is considered to have a negative offset when it is located to the right of the left-turn lane for oncoming traffic on the opposite side of the intersection. A left-turn lane is considered to have a positive offset when it is placed to the left of the left-turn lane for oncoming traffic on the opposite side of the intersection. The difference between negative and positive offset is continuous such that offset is considered positive to the extent that left-turn lanes are positioned left of their counterparts on the opposite side of the intersection. The more positive the offset, the greater the visibility of oncoming traffic should be for a driver planning to execute a left turn. The greater visibility of positive offset could be expected to lower the frequency of collisions between vehicles turning left and oncoming vehicles.

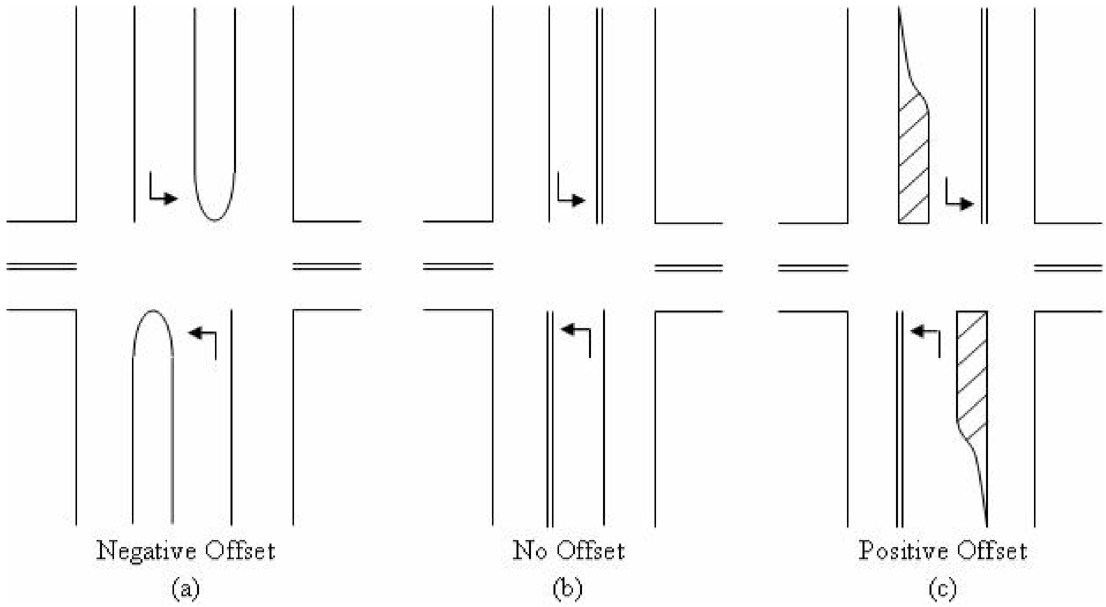

Figure 21. Intersections featuring left-turn lanes with negative offset, no offset, and positive offset.

Persaud, Lyon, Eccles, and Gross (2009) reported mixed results in a study examining intersections in Nebraska, Florida, and Wisconsin before and after the introduction of modifications aimed at increasing the offset of left-turn lanes. Surprisingly, there was some evidence that offsetting opposing left-turn lanes to the right can increase the number of collisions. However, it is important to consider that the offset achieved by merely shifting the opposing left-turn lane to the right does not necessarily achieve the goal of providing drivers an unobstructed view of oncoming traffic (see Figure 20). In Nebraska, offsetting the left turn lanes actually resulted in more collisions, but few of the modifications were extreme enough to result in positive offset. Modifications were more extreme in Wisconsin, transforming most intersections to a positive offset, which may help to explain why modifications resulted in fewer collisions in this state. Guerrier and Fu (2002) had drivers evaluate conventional and offset left-turn lanes in the Miami, FL area, asking them to rate visibility of oncoming traffic, ease of gap judgments, and comfort in making left turns. Urging readers to consider that their sample of intersections was limited, they concluded “Offset left turn lanes were not found to provide a significantly greater advantage over conventional left turns in this study. This may be because the conditions for which these offset left turn lanes are most appropriate were not encountered in this study” (p. 20). Clearly additional research is needed to determine if and under which conditions the offsetting of left-turn lanes improves visibility and safety relative to the more standard negative offset.

Little is known regarding the efficacy of this practice on the crash rates of older adult drivers and the factors that moderate their crash risk, but there is evidence that older adult drivers accept longer gaps in conditions of negative offset, that is, when visibility of oncoming traffic is presumably poorest (Staplin, Harkey, Lococo, & Tarawneh, 1997). Guerrier and Fu’s (2002) study included older and younger adult participants but did not reveal differences between these groups. Current research is examining this question. If offsetting opposing left turn lanes to the right does not reduce the risk of older adult drivers at intersections, other alternative approaches must be considered to reduce this risk.

We assessed the effects of left turn lane placement and age group in two simulator studies. In Task 3a, the car was situated in a left-turn lane that either had a large negative offset (11.8 feet), or only a minimal negative offset (3.2 feet) and participants were prompted by the sound of a car horn to make speeded responses indicating whether or not it was currently safe to initiate a turn. Of primary interest was whether the decreased negative offset allowed drivers of all ages to make better turn decisions (i.e., turn with enough time so the distance between their own car and any oncoming vehicles was maximum), and whether this configuration was especially beneficial to older drivers. In Task 3b, participants confronted a more realistic scenario inviting them to make simulated left turns. That is rather than making speeded judgments, participants were asked to execute a left-turn when they felt it was safe to do so. Again, minimum distance between the participant's vehicle and oncoming traffic was used as a measure of safety.

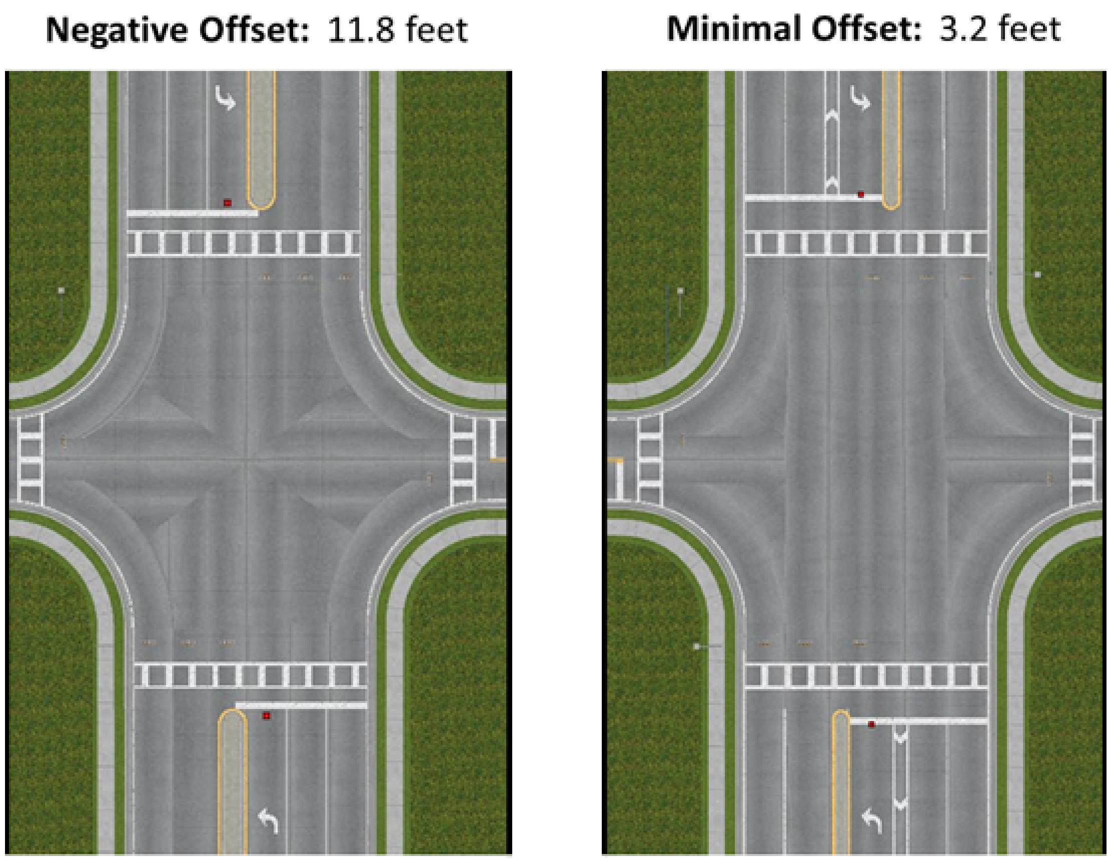

Figure 22. Negative offset (left) and minimal offset (right) left-turn lanes used in Tasks 3a and 3b.

Method

Participants

Overall, 31 older, 28 middle-aged, and 36 younger adults were recruited for the study. Compensation for completing the study was $15.

Materials

Tasks 3a and 3b were completed in the driving simulator described above.
In Task 3a, the participant's car was situated in a left-turn lane that either had a large negative offset or a minimal negative offset (see Figure 21), with the type of offset counterbalanced across participants. Participants were presented with a continuous stream of traffic, with varying gaps between cars, and were prompted to make a speeded response every 2.5 or 5.5 seconds (varied randomly within-participants) on whether or not it was currently safe to initiate a turn. Cars were situated in the opposing left-turn lane to make this task especially challenging. Overall, participants were presented with 147 opportunities to make a response. The primary dependent variable in this task was the distance between the participant's vehicle and the nearest oncoming vehicle beyond 10 feet (gap length), which was calculated once participants indicated with a button press that they would make a turn. A 10 foot limit was imposed as it was possible that one or more participants chose to initiate a turn as a car currently in the intersection was exiting the intersection, making the passing vehicle the nearest vehicle, but not the one the participant would be crossing in front of if they actually executed the turn.

Figure 23. Negative offset (above) and minimal negative offset (below) conditions from the driver's view in the simulator. Note that the oncoming white car in the bottom panel would not be visible in the standard (negative) offset condition.

In Task 3b, rather than having participants make speeded judgments, they were asked to execute left turns when they felt that it was safe while driving. Again, minimum distance between the participant's vehicle and oncoming traffic was used as a measure of safety. In this scenario, participants were presented with two negative offset intersections and two minimal offset intersections, all of which required them to execute a left-hand turn in the face of opposing traffic. The presentation order of the intersections was balanced across participants. The primary dependent variables in this task were the participant's vehicle speed (turn speed) and distance to the nearest oncoming vehicle beyond 10 feet (gap length), which were calculated once the participant positioned their vehicle within the lane of opposing through traffic.

For both tasks, the speed of the traffic at the intersection was manipulated. The speed limit was either 35 mph or 45 mph, which will be categorized below respectively as the slow and fast intersection speed conditions. These were the speed limits assigned to participants, but within each scenario, the oncoming vehicles traveled at the same speed. For each participant, the speed limit was different for Task 3a and 3b. For example, a participant who judged whether or not it was safe to turn in the Task 3a scenario, where the oncoming vehicles traveled at the faster speed, would have driven in the Task 3b scenario, where the oncoming vehicles traveled at the slower speed (and vice versa with other participants). This was done to minimize carryover from one task to the next.

Scenarios for Tasks 3a and 3b were modeled in accordance with FDOT Design Standards.

Procedure

Each participant completed Tasks 3a and 3b in a single session that lasted about one hour. Because Task 3b required participants to complete simulated left turns, which pilot testing suggested can induce simulator sickness in some individuals, potential loss of data was minimized by having every participant complete Task 3a prior to Task 3b. Participants were instructed to obey a speed limit that was identical to the speed of the oncoming vehicles. For example, a participant asked to drive in the scenario in which the oncoming vehicles traveled at the faster speed would have been instructed to obey a speed limit of 45 mph.

Results

As expected, some participants had to discontinue the study due to simulator sickness. Others had to be excluded due to misunderstanding task instructions, disregarding task instructions, experimenter error, or equipment failure. For Task 3a, the dropout for younger, middle, and older participants was 1, 5, and 6, respectively. For Task 3b, the dropout for younger, middle, and older participants was 5, 8, and 9, respectively. For Task 3a, this left us with 35 younger (M = 23yr), 23 middle-aged (M = 58yr), and 25 older participants (*M* = 72yr). For Task3b, this left us with33 younger (*M* = 22 yrs), 20 middle-aged participants (*M* = 59 yrs), and 22 older participants (*M* = 72 yrs). Although more middle and older participants were excluded from analyses, the number of excluded participants was still small compared to the complete sample size and so would be unlikely to have a significant effect on overall study findings.

Gap Length in Task 3a

As a reminder, gap length in 3a was calculated as the distance (in feet) from the oncoming vehicle when drivers indicated it was safe to turn. Table 9 displays summary statistics for gap length as a function of age group, vehicle speed, and intersection type. To assess the impact that age, oncoming vehicle speed, and intersection type had on gap length, gap length was submitted to a 2x2x3 between-subjects ANOVA using age group (younger vs. middle vs. older), intersection type (negative offset vs. minimal offset), and oncoming vehicle speed (slow vs. fast) as factors. Overall, a main effect of oncoming vehicle speed was found such that participants tended to choose a larger gap length when oncoming vehicles were moving faster as opposed to slower, $F(1, 58) = 13.81$, $p < .001$. No other main effects or interactions reached significance at the .05 level.

Table 9. Task 3a summary statistics for gap length as a function of age group and oncoming vehicle speed.

	Mean			Standard Deviation			Participant Count		
	Neg.	Min.	Overall	Neg.	Min.	Overall	Neg.	Min.	Overall
Age Group									
Younger	371	397	384	63	87	76	17	18	35
Middle	360	346	353	69	77	72	12	11	23
Older	361	315	341	89	114	100	14	11	25
Veh. Speeds									
Fast	400	400	400	31	49	71	22	17	39
Slow	329	333	331	25	55	80	21	23	44
Overall	365	362	364	71	95	83	43	40	83

Gap Length in Task 3b

Gap length in Task 3b was the distance between the closest oncoming vehicle and the participant's car when the participant's car entered the stream of opposing traffic. Table 10 displays summary statistics for gap length as a function of age group, intersection type, and oncoming (and participant) vehicle speed. In order to assess the impact that age, intersection type, and oncoming vehicle speed had on gap length, gap length was submitted to a 2x2x3 mixed ANOVA using age group (younger vs. middle, vs. older) and oncoming vehicle speed (fast vs. slow) as between-subjects factors, and intersection type as a within-subjects factor. Overall, a main effect was found for both age group, $F(2, 67) = 5.06$, $p = .01$, and intersection type, $F(1, 67) = 10.45$, $p < .01$. Follow-up t-tests for the age group factor found that younger participants tended to select a smaller gap length than both middle-, $t(49) = 2.53$, $p = .02$, $d = .73$, and older-aged participants, $t(51) = 2.83$, $p = .01$, $d = .79$. Middle-aged and older participants tended to accept similar gap lengths, $t(40) = -.97$, $p = .34$, $d = .30$. For intersection type, participants chose a greater gap length for the intersections that featured the minimal negative offset lanes compared to the intersections that featured the large negative offset lanes, $d = .44$. No other main effects or interactions reached significance at the .05 level, though a 3-way interaction between age group, intersection type, and oncoming vehicle speed approached significance at the .06 level. This interaction appeared to be driven by lane offset having little effect in the higher speed condition for older adults (see Figure 23).

Table 10. Task 3b summary statistics for gap length as a function of age group, oncoming vehicle speed, and intersection type.

	Mean			Standard Deviation			
	Neg.	Min.	Overall	Neg.	Min.	Overall	Participant Count
Age Group							
Younger	206	234	220	86	51	72	31
Middle	238	279	258	55	46	54	20
Older	254	308	281	154	95	129	22
Veh. Speeds							
Fast	238	271	255	122	59	97	41
Slow	217	266	241	81	89	88	32
Overall	229	269	249	106	73	93	73

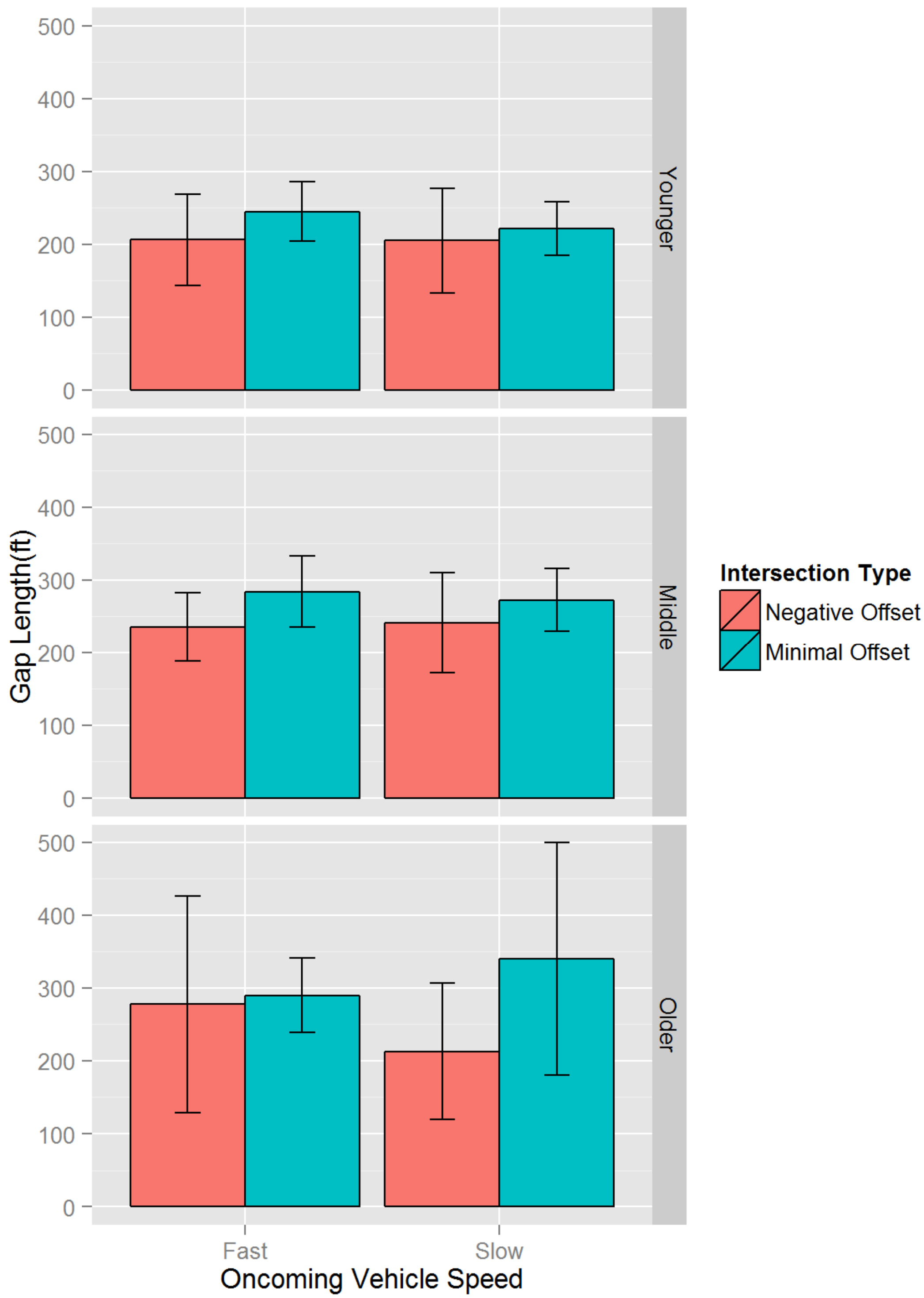

Figure 24. Gap length as a function of vehicle speed, intersection type, and age group. Error bars represent 95% confidence intervals.

Turn Speed in Task 3b

Table 11 displays summary statistics for turn speed as a function of age group, intersection type, and oncoming (and participant) vehicle speed. Turn speed was submitted to a 2x2x3 mixed ANOVA using age group (younger vs. middle, vs. older) and oncoming vehicle speed (slow vs. fast) as between-subjects factors, and intersection type (negative offset vs. minimal offset) as a within-subjects factor. Overall, no main effects or interactions reached significance at the .05 level. In general, although the speed limits for the scenarios were different for participants, speed tended to be slow during turns.

Table 11. Task 3b summary statistics for turning speed as a function of age group, oncoming vehicle speed, and intersection type.

	Mean			Standard Deviation			
	Neg.	Min.	Overall	Neg.	Min.	Overall	Participant Count
Age Group							
Younger	18.17	17.30	17.74	3.16	3.18	3.17	31
Middle	17.80	18.16	17.98	2.90	2.76	2.80	20
Older	16.21	16.16	16.18	3.16	3.84	3.48	22
Veh. Speeds							
Fast	17.74	17.79	17.76	3.09	2.88	2.97	41
Slow	17.14	16.43	16.78	3.28	3.75	3.51	32
Overall	17.48	17.89	17.33	3.17	3.34	3.24	73

Eye Movements and Driving Behavior in Task 3b

For the eye tracking video data, participants were coded on a number of variables. These included whether or not they gazed towards the oncoming straight lane during the turn; that is, the lane that contained the opposing traffic, if they gazed towards the right crossroad; that is, if they gazed down the arm of the intersection located to their right, and whether or not they made a non-stop turn; that is, if they entered the left-hand turn lane and executed the turn without ever coming to a complete stop. Eye movement variables were coded at the time the participant was considered to be making a left-hand turn; in this case, once they passed the stop bar shown on the pavement of the intersection.

Table 12 displays the coded eye movement behaviors for each of the four turn events. The frequencies for each turn event were submitted to a series of chi-square tests in which age group and each dependent variable were used as factors (4 turn events X 3 dependent variables = 12 tests total). When the chi-square could not be used due to one or more expected values that were less than 5, a Fisher's exact test was used. Overall, only one test reached significance at the .05 level. This was the test comparing age groups on non-stop turns for the 1st-presented (out of the 2 in the scenario) negative offset lane. In this comparison 31% of the middle-aged participants made a non-stop turn, whereas 5% of the younger and none of the older participants did so.

Table 12. Task 3b coded eye movement behaviors for each of the four turn events.

	Looked Towards…					
	Oncoming Straight Ln.		Right Crossroad		Non-Stop Turn	
	Yes	No	Yes	No	Yes	No
Negative Offset Turn						
1st	95.00%	5.00%	17.50%	82.50%	12.24%	87.76%
2nd	97.37%	2.63%	18.42%	81.58%	0.00%	100.00%
Minimal Offset Turn						
1st	92.31%	7.69%	12.82%	87.18%	4.08%	95.92%
2nd	97.30%	2.70%	13.51%	86.49%	0.00%	100.00%

Conclusions

Utilizing a driving simulator, it was found that participants tended to give larger gap lengths to oncoming vehicles on minimal offset left-hand turn lanes compared to negative offset left-hand turn lanes when they were able to control their own vehicle's speed and steering. In addition, traffic speed also impacted accepted gap length in that participants tended to give faster moving oncoming vehicles larger gap lengths than slower moving oncoming vehicles, at least when the participant's own vehicle was stationary and the participant was required to make a speeded decision on whether or not they would execute a turn. Younger participants tended to accept smaller gaps than both middle-aged and older participants. Overall, these results suggest that the use of intersections featuring decreased negative offset left-turn lanes results in safer turns, and potentially lower collision rates between left-turning and oncoming vehicles.

Chapter 5. Summary of the Studies

Benefit of the Project

This project has provided relevant data to aid the formulation of policy and recommendations for the Safe Mobility for Life Program and other FDOT programs and policy related to bicycle safety. Some of the findings with relevant policy implications are:

Task 1.

1) Sharrow and Bicycle Detector pavement markings, and the Bicycle Slippery when Wet sign were poorly understood, even among active bicyclists.
2) Florida's 3 Foot Minimum sign quickly and accurately conveyed its intended message.
3) Share the Road and 3 Foot Minimum signs featuring the sideways profile of a bicycle were more easily understood and recognized compared to signs featuring a rear view depiction of a bicyclist/bicycle.

Task 2.

1) When passing a bicyclist, driver passing distances were smaller when a bike lane was present compared to absent.
2) Driver passing distances were smaller when an oncoming vehicle was present in the opposing lane compared to absent.
3) Driver passing distances were smaller when a single bicyclist was present compared to a group of bicyclists.
4) Passing distance did not vary as a function of driver age.

Task 3 a & b.

1) Regardless of intersection type (negative or minimal offset), younger adults made riskier turns (i.e., they were more willing to enter the intersection with a narrower gap in oncoming traffic) compared to middle-aged and older adults.
2) In general, the minimal offset turn lane encouraged safer turning behavior.
3) However, evidence suggests that the benefit older adults experience as a result of a minimal offset turn lane may be reduced when oncoming vehicles are approaching quickly.

Specific Recommendations Based on Study Findings

1) Task 1 found that the Sharrow and Bicycle Detector markings and the Bicyclist Slippery when Wet sign were poorly understood. Although knowledge of Share the Road and 3 Foot Minimum signs was high (85% correct or greater), accurate knowledge was not universal. Educational campaigns have the potential to increase understanding of bicycle warning signs and pavement markings. Materials like the *Florida Bicycling Street Smarts* booklet, Florida's Driver Handbook, and similar materials should be updated to feature an explanation of markings and signs that even active bicyclists found confusing. These signs and markings include the bicyclist Slippery when Wet sign and the Sharrow and Bicycle Detector pavement markings.

2) To ease comprehension and improve sign legibility, we recommend versions of the 3 Foot Minimum and Share the Road signs featuring the depiction of a sideways profile of a bicycle compared to the rear view of a bicyclist/bicycle.

3) In our studies drivers tended to pass bicyclists with care (with more than 3 feet of clearance), even in the absence of warning signs to encourage this behavior. However, this was under relatively ideal driving conditions with light traffic and wide lanes. It is recommended that future studies begin to assess passing distance (with and without bicycle-related warning signs) under more challenging conditions (high traffic, narrower lanes, poor visibility, conditions of distraction). We found that drivers passed bicyclists with less distance when a bicyclist was within a bike lane. This is consistent with previous research. However, this should not be taken as indicating that bicyclists within bike lanes are less safe; research has demonstrated the effectiveness of bike lanes at improving safety. It does, however, suggest that additional research is necessary to understand the mechanism through which bike lanes improve safety (even though drivers may be passing closer). By understanding the mechanism, it is possible that even more effective countermeasures might be developed.

4) We found, consistent with some but not all of the literature, that reducing the negative offset of left-turn lanes was beneficial to drivers of all ages. When possible, and when relevant (e.g., offset probably has a minimal impact on protected turns), minimal offset or positive offset lanes should be implemented. Our data suggests that, at least for older adults, the benefit of minimal offset lanes may be diminished when traffic is moving quickly. Additional research is necessary to confirm this pattern, but if it holds it would suggest that protected turn lanes may be more beneficial to aging road users in some situations. This should be an area of future research.

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Appendix.

Younger Adults: Speeded Comprehension Accuracy			
	Near	Mid	Far
Bicycle Slippery when Wet	0.94	0.92	0.79
Stop at line for pedestrians and cyclists	0.97	0.90	0.94
Stop at line for pedestrians	0.94	0.92	0.89
Stop for pedestrians and cyclists within crosswalk	0.94	0.94	0.84
Stop for pedestrians within crosswalk	0.97	0.94	1.00
Yield at line for pedestrians and cyclists	0.92	0.92	0.87
Yield at line for pedestrians	0.92	0.87	0.92
Yield to pedestrians and cyclists within crosswalk	0.89	0.95	0.85
Yield to pedestrians within crosswalk	0.68	0.68	0.77

Middle Adults: Speeded Comprehension Accuracy			
	Near	Mid	Far
Bicycle Slippery when Wet	0.97	0.94	0.75
Stop at line for pedestrians and cyclists	0.94	0.89	0.83
Stop at line for pedestrians	0.92	0.86	0.97
Stop for pedestrians and cyclists within crosswalk	1.00	0.89	0.78
Stop for pedestrians within crosswalk	1.00	1.00	0.89
Yield at line for pedestrians and cyclists	0.89	0.86	0.92
Yield at line for pedestrians	0.81	0.86	0.94
Yield to pedestrians and cyclists within crosswalk	0.92	0.86	0.75
Yield to pedestrians within crosswalk	0.61	0.67	0.78

Older Adults: Speeded Comprehension Accuracy			
	Near	Mid	Far
Bicycle Slippery when Wet	0.97	0.92	0.66
Stop at line for pedestrians and cyclists	0.92	0.87	0.87
Stop at line for pedestrians	0.95	0.92	0.95
Stop for pedestrians and cyclists within crosswalk	1.00	0.89	0.58
Stop for pedestrians within crosswalk	0.95	0.95	0.95
Yield at line for pedestrians and cyclists	0.84	0.82	0.95
Yield at line for pedestrians	0.92	0.82	0.95
Yield to pedestrians and cyclists within crosswalk	0.87	0.87	0.89
Yield to pedestrians within crosswalk	0.55	0.63	0.66

Younger Adults: Pattern Matching Accuracy			
	Near	**Mid**	**Far**
Bicycle Slippery when Wet	0.98	0.97	0.75
Stop at line for pedestrians and cyclists	0.92	0.84	0.92
Stop at line for pedestrians	0.92	0.91	0.91
Stop for pedestrians and cyclists within crosswalk	0.89	0.92	0.83
Stop for pedestrians within crosswalk	0.94	0.95	0.86
Yield at line for pedestrians and cyclists	0.89	0.8	0.91
Yield at line for pedestrians	0.94	0.89	0.86
Yield to pedestrians and cyclists within crosswalk	0.91	0.83	0.89
Yield to pedestrians within crosswalk	0.89	0.88	0.84

Middle Adults: Pattern Matching Accuracy			
	Near	**Mid**	**Far**
Bicycle Slippery when Wet	0.94	1.00	0.72
Stop at line for pedestrians and cyclists	0.91	0.94	0.88
Stop at line for pedestrians	0.91	0.94	0.88
Stop for pedestrians and cyclists within crosswalk	0.78	0.81	0.75
Stop for pedestrians within crosswalk	0.94	0.88	0.72
Yield at line for pedestrians and cyclists	0.88	0.78	0.75
Yield at line for pedestrians	0.88	0.88	0.91
Yield to pedestrians and cyclists within crosswalk	0.84	0.88	0.72
Yield to pedestrians within crosswalk	0.94	0.94	0.81

Older Adults: Pattern Matching Accuracy			
	Near	**Mid**	**Far**
Bicycle Slippery when Wet	0.89	0.92	0.67
Stop at line for pedestrians and cyclists	0.86	0.81	0.86
Stop at line for pedestrians	0.92	0.86	0.92
Stop for pedestrians and cyclists within crosswalk	0.86	0.83	0.67
Stop for pedestrians within crosswalk	0.89	0.89	0.75
Yield at line for pedestrians and cyclists	0.83	0.72	0.78
Yield at line for pedestrians	0.86	0.89	0.86
Yield to pedestrians and cyclists within crosswalk	0.89	0.83	0.78
Yield to pedestrians within crosswalk	0.89	0.83	0.72

Speeded Comprehension Accuracy for Pavement Markings			
	Young	**Middle**	**Older**
Bike Lane	.92	.97	.92
Bicycle Crossing	.95	.97	.89
Bicycle Detector	.94	.89	.82
Sharrow	.94	.86	.82

Pattern Matching Accuracy for Pavement Markings			
	Young	**Middle**	**Older**
Bike Lane	.97	.91	.94
Bicycle Crossing	.98	.97	.92
Bicycle Detector	.98	.97	.94
Sharrow	1.00	1.00	1.00

Younger Adults: Speeded Comprehension Response Speed (ms)			
	Near	**Mid**	**Far**
Bicycle Slippery when Wet	1177	1361	2006
Stop at line for pedestrians and cyclists	1489	1497	1482
Stop at line for pedestrians	1324	1451	1469
Stop for pedestrians and cyclists within crosswalk	1399	1454	1761
Stop for pedestrians within crosswalk	1418	1448	1653
Yield at line for pedestrians and cyclists	1416	1480	1617
Yield at line for pedestrians	1320	1321	1370
Yield to pedestrians and cyclists within crosswalk	1532	1633	1694
Yield to pedestrians within crosswalk	1438	1407	1718

Middle Adults: Speeded Comprehension Response Speed (ms)			
	Near	**Mid**	**Far**
Bicycle Slippery when Wet	1923	1870	2755
Stop at line for pedestrians and cyclists	1824	1807	2356
Stop at line for pedestrians	1953	1849	2080
Stop for pedestrians and cyclists within crosswalk	1872	1958	2899
Stop for pedestrians within crosswalk	1697	1786	2399
Yield at line for pedestrians and cyclists	1728	1725	2116
Yield at line for pedestrians	1730	1862	2038
Yield to pedestrians and cyclists within crosswalk	2280	1828	2620
Yield to pedestrians within crosswalk	2046	1968	2796

Older Adults: Speeded Comprehension Response Speed (ms)			
	Near	Mid	Far
Bicycle Slippery when Wet	2273	2088	2273
Stop at line for pedestrians and cyclists	2043	2009	2082
Stop at line for pedestrians	2102	1888	2286
Stop for pedestrians and cyclists within crosswalk	2411	2385	3445
Stop for pedestrians within crosswalk	1800	2166	2933
Yield at line for pedestrians and cyclists	2155	1938	2819
Yield at line for pedestrians	2067	2464	2526
Yield to pedestrians and cyclists within crosswalk	2427	2756	3469
Yield to pedestrians within crosswalk	2105	2200	3126

Younger Adults: Pattern Matching Response Speed (ms)			
	Near	Mid	Far
Bicycle Slippery when Wet	813	1051	1463
Stop at line for pedestrians and cyclists	857	948	1219
Stop at line for pedestrians	851	981	1017
Stop for pedestrians and cyclists within crosswalk	941	922	1263
Stop for pedestrians within crosswalk	844	931	1238
Yield at line for pedestrians and cyclists	937	889	1089
Yield at line for pedestrians	877	969	1056
Yield to pedestrians and cyclists within crosswalk	844	1025	1299
Yield to pedestrians within crosswalk	844	934	1308

Middle Adults: Pattern Matching Response Speed (ms)			
	Near	Mid	Far
Bicycle Slippery when Wet	1093	1504	1978
Stop at line for pedestrians and cyclists	1210	1476	1613
Stop at line for pedestrians	1042	1393	1425
Stop for pedestrians and cyclists within crosswalk	1379	1348	2244
Stop for pedestrians within crosswalk	1206	1236	1865
Yield at line for pedestrians and cyclists	1229	1452	1642
Yield at line for pedestrians	1178	1349	1351
Yield to pedestrians and cyclists within crosswalk	1466	1502	2149
Yield to pedestrians within crosswalk	1360	1334	2160

Older Adults: Pattern Matching Response Speed (ms)			
	Near	**Mid**	**Far**
Bicycle Slippery when Wet	1262	1750	2372
Stop at line for pedestrians and cyclists	1590	1415	1962
Stop at line for pedestrians	1194	1374	1688
Stop for pedestrians and cyclists within crosswalk	1511	1535	2536
Stop for pedestrians within crosswalk	1473	1461	2667
Yield at line for pedestrians and cyclists	1535	1575	1810
Yield at line for pedestrians	1279	1400	1698
Yield to pedestrians and cyclists within crosswalk	1436	1715	2637
Yield to pedestrians within crosswalk	1482	1569	2535

Speeded Comprehension Response Speed for Pavement Markings (ms)			
	Young	**Middle**	**Older**
Bike Lane	1280	2103	2218
Bicycle Crossing	1293	1936	2136
Bicycle Detector	1149	2037	2380
Sharrow	1243	1970	2396

Pattern Matching Response Speed for Pavement Markings (ms)			
	Young	**Middle**	**Older**
Bike Lane	923	1480	1298
Bicycle Crossing	1021	2460	1614
Bicycle Detector	920	1262	1308
Sharrow	843	1052	1434