

# Visual attention in naturalistic scenes across the lifespan

A thesis submitted in partial fulfilment of the requirements of  
Bournemouth University for the degree of Doctor of Philosophy

Victoria Nicholls

# Copyright Statement

This copy of the thesis has been supplied on condition that anyone who consults it is understood to recognise that its copyright rests with its author and due acknowledgement must always be made of the use of any material contained in, or derived from, this thesis.

# Abstract

Visual attentional skills continue to develop through childhood and do not reach maturity until adolescence. On the other end of the spectrum, older adults' visual attentional skills are declining with age. The development and decline of these skills can lead to difficulties in day to day activities such as throwing or catching a ball, cycling, crossing a road, or even maintaining stability when walking. Alongside this, children and older adults are among the most vulnerable groups in road crossing situations, with older adults accounting for almost 50% of road crossing fatalities in the EU. A link has been suggested between visual attentional control skills and the vulnerability of older adults and children to pedestrian accidents but little has been done to investigate this link. In this PhD, I set out to investigate in fine-grained detail the involvement of attentional control skills in road crossing decisions in children, younger, and older adults. To this aim four experiments were run.

The first experiment tested younger adults and children from five to 15 years old in a road crossing situation where participants had to watch videos of road traffic and decide when they could safely cross the road. The participants' eye movements were recorded. I found that younger children made riskier crossing decisions compared to older children and young adults. Younger children were also less able to inhibit attentional capture by distractors and were less able to disengage overt attention from moving targets when the visual load was high.

In the second experiment, I used a similar paradigm with young and older adults. My findings revealed that older adults were less able to inhibit attentional capture by distractors compared to younger adults. Despite this attentional bias, older adults made safe crossing decisions. This experiment involved only one direction of traffic and more complex situations (several traffic directions, different speeds, large field of view) might be more taxing for older people and impact their abilities to make safe crossing decisions.

As such, in the third experiment I used a virtual reality set-up in order to test scenarios of varying complexity. I also tracked the participants' eye movements across a wide field of view (180°). My results showed that older adults were able in simple situations to make safe crossing decisions and they chose larger gaps between vehicles than younger adults. In more complex situations such as when cars travel faster, older adults made more risky crossing decisions.

In experiments one and two, participants looked predominantly at the point where cars appeared on the road and did not overtly follow the cars down the road. This finding suggested a dissociation between overt and covert attention in the context of road-crossing. In order to explore this dissociation and its potential deficit in children and older people, I developed a technique using in conjunction eye-tracking and steady state visually evoked potential (SSVEP). In this paradigm, participants overtly tracked a moving object and covertly monitored the appearance of a new object at the appearance point. I found a drop in the SSVEP power signal prior to the appearance of the second moving object while the participants' eyes were

still overtly tracking the first object. This result suggests during smooth pursuit a decrease in attentional resources allocated to the foveated object when there is a shift of covert attention towards a second object. In future studies, I aim to use this paradigm to explore more precisely the dynamic of overt and covert attention in more realistic scenario and with children and older participants.

This research used novel approaches to address the socially relevant and timely question of pedestrian safety. To this aim, I used a variety of methods ranging from eye-tracking to image processing, EEG and VR, and I developed new techniques tailored to the questions at hand. For the first time, I directly investigated the relationships between visual exploration, road crossing decisions and changes in attentional control through the lifespan. My findings show that children below the age of 10 are less able to inhibit attentional capture by distractors, which increased the risk of unsafe crossing decisions. In similar, simple situations, older adults also show an attentional bias towards distractors, but they maintain the ability to make safe crossing decisions. VR experiments with systematic manipulations of the complexity of the road crossing scene revealed that older adults make riskier crossing decisions in specific situations such as when cars travel quickly, or from different directions. This research furthers our understanding of attentional control through the lifespan as well as providing insights for pedestrian safety. As such, it provides avenues for the development of training and safety guidelines for pedestrians.

# Thesis Structure

This thesis conforms to an ‘integrated thesis’ format in which chapters (Chapters 2–5) consists of articles written in a style that is appropriate for publication in peer-reviewed journals. The initial and final chapters present an introduction and discussion of the field of research undertaken. The articles included in this thesis are at various stages of the publication/review process, and the status of each paper is summarised below. The main text in each chapter is presented as exact replications of the submitted manuscript and inevitably, there is some repetition as a consequence.

# Status of articles from this thesis

Chapter 2 has been published as: Nicholls, V. I., Jean-Charles, G., Lao, J., de Lissa, P., Caldara, R., & Miellel, S. (2019). Developing attentional control in naturalistic dynamic road crossing situations. *Scientific Reports*, *9(1)*, 1-10.

Chapter 3 is in preparation for publication as: Nicholls, V.I., Meso, A.I., Wiener, J., & Miellel, S. (in prep) Ageing with maintained executive functioning abilities is associated with effective compensatory strategies in dynamic perceptual decisions.

Chapter 4 is in preparation for publication as: Nicholls, V.I., Meso, A.I., Miellel, S., & Wiener, J. (in prep) Ageing and executive function decline lead to performance decline in challenging naturalistic road crossing situations.

Chapter 5 has been published as: de Lissa, P., Caldara, R., Nicholls, V., & Miellel, S. (2020). In pursuit of visual attention: SSVEP frequency-tagging moving targets. *PLOS ONE*, *15(8)*, e0236967.

# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Visual attentional control in natural scenes . . . . .	2
1.2	Change in visual attentional control with age . . . . .	6
1.2.1	From childhood to adulthood . . . . .	6
1.2.2	From younger to older adults . . . . .	8
1.3	Impacts on day to day activities . . . . .	11
1.3.1	Children . . . . .	11
1.3.2	Older adults . . . . .	12
1.4	Road crossing abilities . . . . .	14
1.4.1	Children . . . . .	14
1.4.2	Older adults . . . . .	16
1.5	Rationale and scope of thesis . . . . .	18
<b>2</b>	<b>Developing attentional control in naturalistic dynamic road crossing situations</b>	<b>20</b>
2.1	Introduction . . . . .	20
2.2	Methods . . . . .	24
2.2.1	Participants . . . . .	24
2.2.2	Apparatus . . . . .	25
2.2.3	Experimental Design . . . . .	25
2.2.4	Statistical Analyses . . . . .	27
2.3	Results . . . . .	30
2.3.1	Eye Movement Results . . . . .	30
2.3.2	Road-crossing decisions . . . . .	33
2.4	Discussion . . . . .	35
<b>3</b>	<b>Ageing with maintained executive functioning abilities is associated with effective compensatory strategies in dynamic perceptual decisions</b>	<b>39</b>
3.1	Introduction . . . . .	39
3.2	Methods . . . . .	43
3.2.1	Participants . . . . .	43
3.2.2	Apparatus . . . . .	44
3.2.3	Experimental Procedure . . . . .	45
3.2.4	Statistical Analyses . . . . .	46
3.3	Results . . . . .	53
3.3.1	Crossing decisions . . . . .	54
3.3.2	Eye movement results . . . . .	55
3.4	Discussion . . . . .	57

3.4.1	Does ageing with maintained executive function abilities impact on crossing behaviour? . . . . .	58
3.4.2	Does ageing with maintained executive function abilities impact on visual exploration in a naturalistic dynamic scenario? . . . . .	59
3.4.3	Conclusion . . . . .	60

**4 Ageing and executive function decline lead to performance decline in challenging naturalistic road crossing situations 62**

4.1	Introduction . . . . .	62
4.2	Methods – Experiment 1 . . . . .	66
4.2.1	Participants . . . . .	66
4.2.2	Executive function tests . . . . .	67
4.2.3	Walking speed . . . . .	68
4.2.4	Apparatus . . . . .	68
4.2.5	Experimental Procedure . . . . .	69
4.2.6	Statistical analyses . . . . .	71
4.2.7	Experiment Design . . . . .	74
4.3	Results – Executive function tests . . . . .	75
4.4	Results – Experiment 1 . . . . .	77
4.4.1	Impact of car speed on crossing behaviour . . . . .	77
4.4.2	Impacts of cars coming from an obscured view . . . . .	78
4.4.3	Number of lanes . . . . .	78
4.4.4	Near or far lane . . . . .	78
4.5	Discussion – Experiment 1 . . . . .	79
4.5.1	Do OAs and participants with poorer executive functioning abilities show riskier crossing behaviour when task complexity is increased? . . . . .	79
4.5.2	Conditions that impact negatively on crossing behaviour . . . . .	79
4.5.3	Conditions that did not impact on crossing behaviour . . . . .	81
4.5.4	Summary Experiment 1 . . . . .	82
4.6	Introduction – Experiment 2 . . . . .	83
4.7	Methods – Experiment 2 . . . . .	84
4.7.1	Experimental Design . . . . .	84
4.8	Results – Experiment 2 . . . . .	85
4.8.1	Impacts of car speed on crossing behaviour . . . . .	85
4.8.2	Impact of cars coming from both directions on crossing behaviour . . . . .	87
4.8.3	Impact of cars coming from an obscured view on crossing behaviour . . . . .	89
4.8.4	Impact of traffic density on crossing behaviour . . . . .	91
4.8.5	Impact of pedestrian distractors on crossing behaviour . . . . .	92
4.9	Discussion – Experiment 2 . . . . .	92
4.9.1	Do OAs and participants with poorer executive functioning abilities show riskier crossing behaviour when task complexity is increased? . . . . .	92
4.9.2	Conditions that negatively impact on crossing behaviour . . . . .	93
4.9.3	Conditions that do not impact or impact positively on crossing behaviour . . . . .	95
4.10	Conclusion . . . . .	97

<b>5</b>	<b>In pursuit of visual attention: SSVEP frequency-tagging moving targets</b>	<b>99</b>
5.1	Introduction . . . . .	99
5.2	Methods . . . . .	102
5.2.1	Participants . . . . .	103
5.2.2	Stimuli and procedure . . . . .	103
5.2.3	Eye movement recording and processing . . . . .	105
5.2.4	EEG recording and processing . . . . .	110
5.3	Results . . . . .	113
5.4	Discussion . . . . .	114
<b>6</b>	<b>General Discussion</b>	<b>121</b>
6.1	Overview of research findings . . . . .	121
6.2	Discussion of findings . . . . .	124
6.2.1	Discussion on individual chapter findings . . . . .	124
6.2.2	Differences between visual and neural processing involved in naturalistic and lab based experiments . . . . .	130
6.2.3	Specific insights gained from a combined data-driven and hypothesis-driven approach . . . . .	131
6.2.4	Contributions to the road safety literature and recommendations to improve road safety . . . . .	134
6.2.5	Summary of contributions to visual attention and cognitive neuroscience literature . . . . .	136
6.3	Future directions . . . . .	136
6.4	Concluding comments . . . . .	139
<b>A</b>	<b>Supplementary materials for chapter 2</b>	<b>141</b>
A.1	Supplementary Figures . . . . .	141
A.2	Supplementary Results . . . . .	159
A.3	Amendments and response to examiners for Chapter 2 . . . . .	161
A.3.1	Responses to internal examiner . . . . .	178
<b>B</b>	<b>Supplementary materials for chapter 3</b>	<b>183</b>
B.1	Supplementary Figures . . . . .	183
B.2	Supplementary Tables . . . . .	185
B.3	Response to Examiners Comments . . . . .	186
B.3.1	Response to external examiners comments . . . . .	186
B.3.2	Response to internal examiners comments . . . . .	189
<b>C</b>	<b>Supplementary materials for chapter 4</b>	<b>192</b>
C.1	Supplementary Figures . . . . .	192
C.1.1	Relationship between TTI and DTI . . . . .	192
C.1.2	Main effects . . . . .	193
C.1.3	Head Movements . . . . .	194
C.1.4	Duration of key presses . . . . .	195
C.1.5	RMA RT results . . . . .	196
C.1.6	Main effects . . . . .	197
C.1.7	Head Movements . . . . .	197
C.1.8	Duration of key presses . . . . .	200
C.1.9	RMA RT results . . . . .	201
C.2	Supplementary Tables . . . . .	203

C.3	Response to examiners' comments . . . . .	226
C.3.1	Response to external examiner's comments . . . . .	226
C.3.2	Response to internal examiner's comments . . . . .	229
<b>D</b>	<b>Supplementary materials for chapter 5</b>	<b>233</b>
D.1	Supplementary Figures . . . . .	233
D.2	Response to examiner's comments . . . . .	234
D.2.1	Response to external examiner's comments . . . . .	234
D.2.2	Response to internal examiner's comments . . . . .	244
References	. . . . .	245

# List of Tables

2.1	General oculomotor characteristics for children and young adults . . .	30
4.1	Means, bootstrap t-test, and Bayes Factor results for differences between OAs and YAs EF abilities for Chapter 4 . . . . .	75
A.1	Differences in amounts of different oculomotor characteristics for children and young adults . . . . .	169
B.1	Results from the linear mixed model on time to impact for Chapter 3	185
B.2	Results from the simple effects linear mixed model on time to impact for older adults for Chapter 3 . . . . .	185
B.3	Results from the simple effects linear mixed model on time to impact for younger adults for Chapter 3 . . . . .	185
B.4	Results from the linear mixed model on number of crossing decisions for Chapter 3 . . . . .	185
B.5	Results from the simple effects linear mixed model on number of crossing decisions for older adults for Chapter 3 . . . . .	185
B.6	Results from the linear mixed model on the duration of button presses for Chapter 3 . . . . .	186
B.7	Results from the simple effects linear mixed model on the duration of button presses for older adults for Chapter 3 . . . . .	186
B.8	Results from the simple effects linear mixed model on the duration of button presses for younger adults for Chapter 3 . . . . .	186
C.1	Results for the LMM run on the number of crossing decisions for VR Experiment 1 . . . . .	203
C.2	Results for the LMM run on the duration of key presses for VR Experiment 1 . . . . .	204
C.3	Results for the simple effects LMM run on the duration of key presses made by YAs on VR Experiment 1. . . . .	204
C.4	Results for the simple effects LMM on the duration of key presses made by OAs on VR Experiment 1. . . . .	205
C.5	Results for the simple effects LMM run on the duration of key presses made by participants with high BADS zoo map scores on VR Experiment 1. . . . .	205
C.6	Results for the simple effects LMM on the duration of key presses made by participants with low BADS zoo map scores on VR Experiment 1 . . . . .	205
C.7	Results of the LMM run on the number of crossing decisions on VR Experiment 2 . . . . .	206
C.8	Results of the simple effects LMM run on the number of crossing decisions made by YAs on VR Experiment 2 . . . . .	207

C.9 Results of the simple effects LMM on the number of crossing decisions made by OAs on VR Experiment 2 . . . . . 207

C.10 Results of the simple effects LMM on the number of crossing decisions by participants with slow RTs on the RMA task on VR Experiment 2. 207

C.11 Results of the simple effects LMM on number of crossing decisions by participants with fast RTs on the RMA task on VR Experiment 2 . . 208

C.12 Results of the simple effects LMM run on the number of crossing decisions made by participants with high BADS zoo map scores on VR Experiment 2 . . . . . 208

C.13 Results of the simple effects LMM run on the number of crossing decisions made by participants with low BADS zoo map scores on VR Experiment 2. . . . . 208

C.14 Results of the simple effects LMM run on the number of crossing decisions made by participants with large global switch costs on VR Experiment 2. . . . . 209

C.15 Results of the simple effects LMM run on the number of crossing decisions made by participants with small global switch costs on VR Experiment 2. . . . . 209

C.16 Results of the simple effects LMM run on the number of crossing decisions made by participants with large local switch costs on VR Experiment 2. . . . . 209

C.17 Results of the simple effects LMM run on the number of crossing decisions made by participants with small local switch costs on VR Experiment 2. . . . . 210

C.18 Results for the LMM run on duration of key presses on VR Experiment 2 . . . . . 211

C.19 Results of the simple effects LMM run on the duration of key presses made by YAs on VR Experiment 2. . . . . 211

C.20 Results of the simple effects LMM run on the duration of key presses made by OAs on VR Experiment 2. . . . . 212

C.21 Results of the simple effects LMM on the duration of key presses made by participants with slow RTs on the RMA task on VR Experiment 2. 212

C.22 Results of the simple effects LMM on the duration of key presses by participants with fast RTs on the RMA task on VR Experiment 2. . . 212

C.23 Results of the simple effects LMM on the duration of key presses made by participants with large global switch costs on VR Experiment 2. . 213

C.24 Results of the simple effects LMM on the duration of key presses made by participants with small global switch costs on VR Experiment 2. . 213

C.25 Results of the simple effects LMM on the duration of key presses made by participants with large local switch costs on VR Experiment 2. . . . . 213

C.26 Results of the simple effects LMM on the duration of key presses made by participants with small local switch costs on VR Experiment 2. . . 214

C.27 Results for the LMM run on TTI for VR Experiment 1 . . . . . 215

C.28 Simple effects LMM run on the TTI for YAs on VR Experiment 1. . . 215

C.29 Simple effects LMM on the TTI for OAs on VR Experiment 1. . . . 216

C.30 Simple effects LMM on the TTI for participants with low BADS zoo map scores on VR Experiment 1. . . . . 216

C.31 Simple effects LMM on the TTI for participants with high BADS zoo map scores on VR Experiment 1. . . . . 216

C.32	Simple effects LMM on the TTI decisions for participants with fast RTs on the RMA task on VR Experiment 1. . . . .	216
C.33	Simple effects LMM on TTI decisions for participants with slow RTs on the RMA task on Experiment 1. . . . .	217
C.34	Results for the LMM on TTI on VR Experiment 2 . . . . .	218
C.35	Simple effects LMM run on the TTI for YAs on VR Experiment 2. . . . .	218
C.36	Simple effects LMM run on the TTI for OAs on VR Experiment 2. . . . .	219
C.37	Simple effects LMM run on the TTI for participants with small local switch costs on VR Experiment 2. . . . .	219
C.38	Simple effects LMM run on the TTI for participants with large local switch costs on VR Experiment 2. . . . .	219
C.39	Simple effects LMM run on the TTI for participants with high BADS zoo map scores on VR Experiment 2. . . . .	219
C.40	Simple effects LMM run on the TTI for participants with low BADS zoo map scores on VR Experiment 2. . . . .	220
C.41	Results for the LMM run on the amount of head movements participants made on VR Experiment 1 . . . . .	220
C.42	Simple effects LMM run on the amount of head movements made by participants with small local switch costs on VR Experiment 1 . . . . .	221
C.43	Simple effects LMM run on the amount of head movements made by participants with large local switch costs on VR Experiment 1 . . . . .	221
C.44	Results for the LMM run on the amount of head movements participants made on VR Experiment 2 . . . . .	222
C.45	Simple effects LMM run on the amount of head movements made by YAs on VR Experiment 2 . . . . .	223
C.46	Simple effects LMM run on the amount of head movements made by OAs on VR Experiment 2. . . . .	223
C.47	Simple effects LMM on head movements for participants with fast RTs on the RMA task on Experiment 2. Significant results are highlighted in blue. See Methods for the model that was run. . . . .	223
C.48	Simple effects LMM on head movements for participants with slow RTs on the RMA task on Experiment 2. See Methods for the model that was run. . . . .	224
C.49	Simple effects LMM run on the amount of head movements made by participants with low BADS zoo map scores on VR Experiment 2. . . . .	224
C.50	Simple effects LMM run on the amount of head movements made by participants with high BADS zoo map scores on VR Experiment 2. . . . .	224
C.51	Simple effects LMM run on the amount of head movements made by participants with small global switch costs on VR Experiment 2. . . . .	225
C.52	Simple effects LMM run on the amount of head movements made by participants with large global switch costs on VR Experiment 2. . . . .	225
C.53	Simple effects LMM run on the amount of head movements made by participants with small local switch costs on VR Experiment 2 . . . . .	225
C.54	Simple effects LMM run on the amount of head movements made by participants with large local switch costs on VR Experiment 2 . . . . .	226

# List of Figures

2.1	Example of the video stimuli and illustration of the eye parser algorithm	27
2.2	Gaze similarity figures for children and young adults . . . . .	31
2.3	Statistical gaze maps for children and young adult . . . . .	33
2.4	Crossing decisions for children and young adults . . . . .	34
3.1	Illustration of the car detection algorithm . . . . .	49
3.2	Illustration of the eye movement parser algorithm . . . . .	50
3.3	Crossing decisions for older and younger adults in Chapter 3 . . . . .	55
3.4	Gaze similarity matrices for older and younger adults . . . . .	56
3.5	Statistical gaze maps for older and younger adults . . . . .	57
4.1	Example three screen calibration stimuli . . . . .	69
4.2	VR experiment set up and stimulus . . . . .	70
4.3	Conditions for VR Experiment 1 . . . . .	74
4.4	Executive function results for Chapter 4 . . . . .	76
4.5	Car speed and crossing decisions for VR Experiment 1 . . . . .	77
4.6	The effect of cars coming from an obscured view on crossing decisions for VR Experiment 1 . . . . .	78
4.7	Conditions for VR Experiment 2 . . . . .	85
4.8	The effect of car speed on the crossing decisions on VR Experiment 2	87
4.9	The effect of cars coming from both directions on crossing decisions for VR Experiment 2 . . . . .	89
4.10	The effect of cars coming from an obscured view on the crossing de- cisions on VR Experiment 2 . . . . .	91
4.11	The effect of traffic density on the crossing decisions on VR Experi- ment 2 . . . . .	92
5.1	SSVEP experiment design . . . . .	104
5.2	Eye position in relation to target on SSVEP experiment . . . . .	109
5.3	Scalp topographies during SSVEP experiment . . . . .	112
5.4	30 Hz power (ERSP) across the trial period for the SSVEP experiment	114
A.1	Density figure of trials with each number of cars present . . . . .	141
A.2	Shift functions for number of fixations with pedestrian presence . . .	142
A.3	Shift functions for the number of smooth pursuits with pedestrian presence . . . . .	143
A.4	Shift functions for the number of saccades with pedestrian presence .	144
A.5	Shift functions for the median duration of fixations with pedestrian presence. . . . .	145
A.6	Shift functions for the median duration of smooth pursuits with pedes- trian presence . . . . .	146

A.7	Shift functions for the median duration of saccades with pedestrian presence . . . . .	147
A.8	Shift functions for the proportion of trial time as fixation with pedestrian presence . . . . .	148
A.9	Shift functions for the proportion of trial time as smooth pursuit with pedestrian presence . . . . .	149
A.10	Shift functions for the proportion of trial time as saccades with pedestrian presence . . . . .	150
A.11	Shift functions for the number of fixations with traffic density . . . .	151
A.12	Shift functions for the number of smooth pursuits with traffic density	152
A.13	Shift functions for the number of saccades with traffic density . . . .	153
A.14	Shift functions for the median fixation duration for traffic density . .	154
A.15	Shift functions for the median smooth pursuit duration for traffic density . . . . .	155
A.16	Shift functions for the median saccade duration for traffic density . .	156
A.17	Shift functions for the proportion of trial time as fixation with traffic density . . . . .	157
A.18	Shift functions for the proportion of trial time as smooth pursuit with traffic density . . . . .	158
A.19	Shift functions for the proportion of trial time as saccades with traffic density . . . . .	159
A.20	Updated bootstrapped GSM figure panel . . . . .	170
B.1	Results for each executive function measure for older and younger adults for Chapter 3 . . . . .	184
C.1	The relationship between TTI and DTI when cars travelled quickly compared to slowly. . . . .	192
C.2	Main effects on VR Experiment 1 . . . . .	193
C.3	Head movement results for VR Experiment 1 . . . . .	194
C.4	Key press duration results for VR Experiment 1 . . . . .	195
C.5	RMA RT results for VR Experiment 1 . . . . .	196
C.6	Main effects on VR Experiment 2 . . . . .	197
C.7	Head movement results for VR Experiment 2 . . . . .	198
C.8	Key press duration results for VR Experiment 2 . . . . .	200
C.9	RMA RT results for VR experiment 2 . . . . .	201
C.10	Example three screen calibration stimuli . . . . .	226
D.1	Excluded trials from SSVEP experiment . . . . .	233
D.2	Distortions removed by ICA in the SSVEP experiment . . . . .	234

# Acknowledgements

To start with I'd like to thank Dr Sebastien Miellet, thanks for everything senior colleague. Thanks for sticking with me despite being on the other side of the planet. Thanks for always being supportive, kind, patient, and always having a joke ready both as a supervisor or as a friend. Thanks for getting me out to another part of the world I never thought I would see, Australia made a big impact on me. Thanks also for showing me that it's possible to take it easy and have a life outside of academia even when doing a PhD. I had not thought so much about it before starting the PhD and I feel a bit more rounded because of it.

To Prof. Jan Wiener, thank you for taking me on after Seb left, thank you for being patient and being there when I needed help here and there. Thank you for integrating me into your lab with the Wayfinding lab meetings and putting up with my rants on statistics and bar plots. I know I have not always been the easiest of students to handle so I really appreciate your patience, encouragement and willingness to work with me.

To Dr Andrew Meso, thank you for sticking around for most of the journey and I'm sorry you had to leave towards the end. Thank you for your long conversations over coffee or in the pub you always had great advice and different ways to approach problems which I don't think I always understood in the way you intended. However, I appreciate the way you think about things and how different they were to what I was used to, I think it did help me see problems in another way.

To the guys in Australia, Maryann W, Sam, Ellie, Maryann S, Emily, Jack, and others, thanks for welcoming me into the UOW family and being willing to stay in touch even when I'm so far away. To Dr Sam Moreton thank you for welcoming me into your friend family, and taking me bodyboarding and showing me what it means to be Australian, also for many a subway. Thank you to Maryann W. for regular 3pm beers, love and great conversation, and unique ways to maintain a friendship when geographically separated.

To the BU PhD guys thanks for being there and providing some great times, good celebrations and good wallowing over PhDs or Brexit. Especially I want to thank Chris for always being willing to go for a beer or coffee either just to chat about something or lead into a longer evening depending on what either of us needed. It was great to have someone there going through very similar things and I could share anything and everything with. Also thanks for taking me to Download, always great times.

To my family, thank you for always being at the end of a phone call if I needed it and providing me with as much support and kind words as possible. Thank you also to my brother Dr Simon Nicholls for help with some calculations here and there and for general advice on how to do a PhD.

Thanks for everything. *Per aspera ad inferi.*

# Declaration

I hereby declare that the work presented in this thesis has not been and will not be, submitted in whole or in part to another University for the award of any other degree.



# Chapter 1

## Introduction

To perform an everyday task such as road crossing one has to have an idea of where to focus one's attention to take into account the right information for the task and to filter out distracting parts of the environment such as other pedestrians, or redundant parts of the environment such as trees. Where our attention is focused during a task is the result of an interplay between features of the environment e.g. brightness, colour, object shape, that attract attention (bottom-up processes, Borji, Sihite, & Itti, 2013; Bruce & Tsotsos, 2006, 2009; Itti & Koch, 2001; Marat et al., 2009; Wolfe, 1998) and our own knowledge of how to solve the task and therefore where we think we should allocate our attention to solve the task (top-down processes, Henderson, Weeks Jr, & Hollingworth, 1999; Loftus & Mackworth, 1978; S. E. Palmer, 1975; Tatler, Hayhoe, Land, & Ballard, 2011; Wolfe, Vö, Evans, & Greene, 2011). The ability to focus our attention on areas of the environment is known as attentional control (W. Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). In this chapter I will describe how these bottom-up and top-down processes influence where we look and how we behave during a task, when viewing both simple and naturalistic stimuli. I will then discuss how top-down and bottom-up processes, as well as the interplay between them change from childhood to adulthood, and from younger to older adulthood. From there I will discuss how these developmental and age-related changes might affect day to day activities for children and older adults. The chapter then finishes with the thesis rationale.

## 1.1 Visual attentional control in natural scenes

Basic visual features can capture and guide visual attention (Wolfe, 1998). For example, if a target differs from a set of distractors on a single feature dimension, e.g. colour or orientation, it can be detected very rapidly (Treisman & Gelade, 1980). The capture of attention by these basic visual features can be used to predict a greater than chance number of eye movements in tasks such as visual search in complex visual scenes (Itti & Koch, 2000; Parkhurst, Law, & Niebur, 2002), at least when the target is defined by simple visual features (Tatler et al., 2011). When the task is altered for example from a gazing at a picture for a memory task to a search task these basic visual features, e.g. colour or orientation, become less predictive of eye movement behaviour (Foulsham & Underwood, 2007, 2008; Henderson, Brockmole, Castelhana, & Mack, 2007; Underwood, Foulsham, van Loon, Humphreys, & Bloyce, 2006). The eye movements are then better predicted by object level information e.g. chairs or cars (Einhäuser, Spain, & Perona, 2008; Tatler & Vincent, 2009).

Most of the past research on attentional control has used tightly controlled experimental paradigms, but in recent years doubts have been raised over the extent to which these findings generalize to the “real” world (Kingstone, Smilek, & Eastwood, 2008; Smilek, Birmingham, Cameron, Bischof, & Kingstone, 2006). When increasing the realism of the stimuli to include dynamic scenes, basic visual features such as colour, intensity, and orientation contrasts had the lowest prediction accuracy for the location of fixations participants made (Carmi & Itti, 2006). However, basic visual features such as motion were highly predictive of fixation locations, more so than basic visual features predicted fixations in static stimuli (Carmi & Itti, 2006; Mital, Smith, Hill, & Henderson, 2011; T. J. Smith & Mital, 2013; T. J. Smith, 2013). From these studies it would seem that basic visual features are more predictive of gaze behaviour in dynamic scenes than in static scenes. However, in dynamic stimuli such as films, it is difficult to separate the influence of basic visual features from visual features that are cognitively relevant. For example, fixations may land on moving faces, hands, or vehicles but these objects are also semantically relevant

to the task (Henderson et al., 2007; Henderson, Chanceaux, & Smith, 2009; Mital et al., 2011; T. J. Smith & Mital, 2013; Torralba, Oliva, Castelhana, & Henderson, 2006).

However, experimental context that use simple visual displays or videos share little resemblance with the complex and dynamic environments we typically find ourselves in (Risko, Laidlaw, Freeth, Foulsham, & Kingstone, 2012). For example, in the “real” world it is very rare to search for the same target over and over again as most of our day-to-day activities involve navigating through complex visual environments, whilst inhibiting many different distractors simultaneously (Kuhn & Teszka, 2017). Indeed, when walking through real or virtual environments, models based on basic visual features predict that the majority of fixations would land on the background. However, when participants performed such tasks only 15% of fixations landed in the background (Rothkopf, Ballard, & Hayhoe, 2007). This difference between predicted and actual eye movement behaviour is even more discernible in ball sports. In ball sports saccades were launched to regions where the ball would arrive in the near future even though there were no features that distinguished these locations from the background (Ballard & Hayhoe, 2009; Land & McLeod, 2000).

Many studies show a link between where individuals look during the task and the information that is necessary to complete immediate task goals (Epelboim et al., 1995; Hayhoe, Shrivastava, Mruczek, & Pelz, 2003; Land & Furneaux, 1997; Land, Mennie, & Rusted, 1999; Patla & Vickers, 1997; Pelz & Canosa, 2001). This link is accentuated when engaged in a natural, dynamic, interactive task as the majority of fixations fall on task-relevant objects (Hayhoe et al., 2003; Land et al., 1999). However, before starting the task fixations fall equally between task relevant and irrelevant objects (Hayhoe et al., 2003; Rothkopf et al., 2007). To understand the principles that underlie fixation selection, we must consider eye movements in the context of image features that capture attention (bottom-up stimulation, Borji et al., 2013; Bruce & Tsotsos, 2006, 2009; Itti & Koch, 2001; Marat et al., 2009), and behavioural goals where the requirement is to seek out relevant information at a time when it is needed (top-down influences, Henderson et al., 1999; Loftus &

Mackworth, 1978; S. E. Palmer, 1975; Tatler et al., 2011; Wolfe et al., 2011).

The focus on top-down processes has been of increasing interest in the last 20 years, as the study of visual processes has sought to involve more natural conditions and realistic stimuli. Many recent studies used static and dynamic scenes and included eye movement recordings to look at the influence of context on visual attention (Eckstein, Drescher, & Shimozaki, 2006; Henderson, Chanceaux, & Smith, 2009; Henderson, Malcolm, & Schandl, 2009; Malcolm & Henderson, 2010; T. J. Smith & Mital, 2013; T. J. Smith, 2013; Vö & Henderson, 2010; Wolfe et al., 2011). For instance, these studies have shown influences of semantic knowledge (A. D. Hwang, Wang, & Pomplun, 2011), episodic top-down processes (Castelhano & Henderson, 2007; Castelhano & Heaven, 2011; Vö & Wolfe, 2012), as well as scene context on parafoveal processing of objects (Castelhano & Pereira, 2018; Pereira & Castelhano, 2014; T. J. Smith & Mital, 2013; T. J. Smith, 2013). More recently, the role of the observer's intention and their understanding of the scene has been emphasized (static scenes: Hayes & Henderson, 2017; Henderson, 2017, dynamic scenes: T. J. Smith & Mital, 2013; T. J. Smith, 2013). In this perspective, oculomotor planning is seen as making predictions about the locations of diagnostic information for the task (Friston, Adams, Perrinet, & Breakspear, 2012). The execution of saccades and fixations are then used to process information to check these predictions. This prediction and checking process allows for faster information processing as not all information in the scene is sampled.

Currently, there is a fairly strong consensus that, while low-level visual features such as abrupt onset can account for some portion of people's eye movement behaviour, relevant content is more powerful in explaining visual attention allocation (Foulsham & Underwood, 2008; Tatler et al., 2011).

During natural tasks we are often moving around and walking. The eye-movement system thus encounters different demands compared to sitting still in the laboratory, which is reflected in qualitatively different oculomotor behaviour (Foulsham, Walker, & Kingstone, 2011; 't Hart et al., 2009; 't Hart & Einhäuser, 2012). For example, keeping the eyes on a target that is stationary in the world turns a fixation in

the laboratory into a tracking eye movement during self-motion (Niemann, Lappe, Büscher, & Hoffmann, 1999). Likewise, smooth-pursuit eye-movements as performed in the laboratory are often accompanied by head movements and vestibular-ocular reflexes during free real-world movement (Niemann et al., 1999). Therefore, individuals have to make eye movements that integrate self-motion information in order to take in and process information accurately. At the cortical level, this leads to an involvement of areas of the dorsal pathway where the processing of self-motion signals primarily takes place (Bremmer, Duhamel, Ben Hamed, & Graf, 2000). Especially areas such as the ventral intraparietal area (Bremmer et al., 2001; Bremmer, Duhamel, Ben Hamed, & Graf, 2002; Britten, 2008; A. Chen, DeAngelis, & Angelaki, 2011; Wall & Smith, 2008) and the medial superior temporal area (Bremmer, Kubischik, Pekel, Lappe, & Hoffmann, 1999; Duffy & Wurtz, 1991; Gu, Angelaki, & DeAngelis, 2008; Pitzalis et al., 2013) are activated not only by visual but also by vestibular self-motion signals.

In this section, I have discussed research that has focused on overt attention, but covert attention may also be involved in the processing of natural scenes. Some research has suggested that overt (i.e., attention not independent of eye movements) and covert attentional orienting (i.e., attention that is independent of eye movements) are intrinsically linked (Rizzolatti, Riggio, Dascola, & Umiltá, 1987). While other research suggests that overt and covert attention may be driven by different mechanisms (D. T. Smith & Schenk, 2012). In support of this latter view, Kuhn, Teszka, Tenaw, and Kingstone (2016) have shown that within a more naturalistic context (watching a magic trick), people have more direct top-down control over where they look than where they attend to covertly. In natural scenes such as busy streets we are often monitoring multiple objects at the same time. Monitoring multiple objects involves attention directed to what we are directly foveating on (overt attention), as well as attention directed to areas outside our foveal fields in our parafoveal or peripheral visual fields in the form of covert attention (Kuhn & Teszka, 2017; Posner, 1980).

The biological processes involved in an individual's ability to control their visual

attention changes over the lifespan. The biological processes are still maturing during childhood and they decline in older age which can impact on day to day activities as discussed below.

## **1.2 Change in visual attentional control with age**

### **1.2.1 From childhood to adulthood**

#### **Psychophysics**

During childhood the top-down processes involved in visual attentional control are still maturing along with the frontal brain regions that are considered to control top-down processes (Booth et al., 2003; Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Durston et al., 2002; K. Hwang, Velanova, & Luna, 2010; Kastner & Ungerleider, 2000; Konrad et al., 2005). The maturation of the frontal lobes has been associated with a lack of top-down attentional control (Colombo, 2001) and a deficit of top-down inhibition of reflexive, automatic saccades (Munoz & Everling, 2004; Paus, 1989). These results are consistent with research showing more express saccades, a slower pro- and anti-saccade reaction time and a higher error rate in the anti-saccade tasks for children compared to adults (Fukushima, Hatta, & Fukushima, 2000; Klein, Fischer, Hartnegg, Heiss, & Roth, 2000; Klein & Foerster, 2001; Munoz, Broughton, Goldring, & Armstrong, 1998).

In terms of a critical age at which children reach adult-like performance of their visual attentional control, 8 to 10 years old (y/o) has been consistently suggested in the literature. For example, children between 6 and 8y/o fail to inhibit attentional capture, while 10y/os succeed (Leclercq & Siéroff, 2013). This suggests a critical age of 10 y/os, beyond which children show adult-like performance at inhibiting attentional capture by distractors. Even so, adults have been shown to exhibit faster saccades and fewer prosaccades during the anti-saccade task than 10-11y/os, who in turn had faster saccades and fewer prosaccades than 6 and 7 y/os, showing that the ability to inhibit attentional capture by goal irrelevant stimuli continues to develop throughout childhood (Klein et al., 2000; Klein & Foerster, 2001). The development

of the ability to inhibit attentional capture to goal irrelevant distractors has been associated with a maturation of the frontal lobes (K. Hwang, Ghuman, Manoach, Jones, & Luna, 2016; Munoz & Everling, 2004).

Looking at the development of covert and overt attention, children are able to perform covert attention tasks from 3 y/o (Enns, 1990). This ability, however, does not mature fully until 10-11y/o (Brodeur & Enns, 1997; Enns & Brodeur, 1989; Goldberg, Maurer, & Lewis, 2001; Schul, Townsend, & Stiles, 2003; Waszak, Li, & Hommel, 2010). For example, through manipulating the frequency by which the targets appeared in a peripherally cued location, it was found that children below 8 y/o generally fail to orient attention towards a predictable, yet not cued location (Leclercq & Siéroff, 2013). However, by 10y/o this ability to override an exogenous cue becomes adult-like. Additionally, 6 to 8 y/o children were not able to incorporate endogenous (goal-driven) covert orienting to take advantage of the predictability of a peripheral cue suggesting that children struggle to control their covert attention in a top-down manner (Enns & Brodeur, 1989).

### **Naturalistic scenes**

Most of the studies addressing maturation of visual attentional control have used very simple stimuli involving flashing lights of different colours, and a simple task such as inhibiting attentional capture by a distractor. For more naturalistic stimuli participants typically need to do more than just inhibit attentional capture by distractors. Participants also need to decide which features of a scene they need to focus on to get enough information to complete the task. To determine which features children, young, and older adults focus on Açık, Sarwary, Schultze-Kraft, Onat, and König (2010) presented them with images of natural, and man-made scenes, as well as fractals, followed by an image patch where participants had to determine whether the image patch belonged to the image presented previously. Using receiver operating characteristics (ROC) curves they were able to determine whether participants relied more on top-down or bottom-up processes. Açık et al. (2010) found that younger adults and older children tend to rely on top-down processes rather than bottom-up processes. Children below the age of 9, meanwhile,

tend to focus on bottom-up processes rather than top-down processes (Açık et al., 2010).

Within a naturalistic, dynamic, context research has shown that children below the age of 10 are more distracted than adults and this influences how they experience the world around them (Kuhn & Teszka, 2017). As children 10y/o and above performed similarly to adults in more natural tasks it would seem that this is the critical age for adult-like performance on naturalistic tasks. This critical age of 8-10y/o is the same as that seen in psychophysics tasks, for example in the anti-saccade task (Munoz & Everling, 2004).

In addition to children being less able inhibit their attention being captured by distractors, young children show deficits when they are asked to modify allocation of attention according to complex task demands, compared to single-task baselines. Young children's responses did not change with task demands (Irwin-Chase & Burns, 2000). Children not responding to task demands could cause problems for children in situations that involve complex task demands such as road crossing.

As discussed above, our ability to control visual attention is still developing during childhood but it also deteriorates with older age.

## **1.2.2 From younger to older adults**

### **Psychophysics**

There are a large number of changes to the visual system that occur with age – older adults (OAs) show a decrease in acuity, contrast sensitivity, retinal illumination (Weale, 1961), accommodation of the lens, increased susceptibility to glare, and peripheral field loss (Fozard & Gordon-Salant, 2001; Mackworth, 1965), or a reduced field of view (Ball, Beard, Roenker, Miller, & Griggs, 1988; Sanders, 1970; Scialfa, Kline, & Lyman, 1987; Sekuler & Ball, 1986). In addition, healthy ageing affects both attentional and perceptual contributions to extrafoveal processing (Hartley & McKenzie, 1991). Older adults have more perceptual difficulties in low luminance (Chrysler, Danielson, & Kirby, 1996; Kline et al., 1992; Sivak, Olson, & Pastalan, 1981) and show decreased smooth-pursuit gain (Moschner & Baloh, 1994; Ross et

al., 1999).

These age-related deficits in attentional control have contributed to OAs performing less well than younger adults (YAs) in perception and memory tasks (Açık et al., 2010; Cerella & Hale, 1994; Plude, Enns, & Brodeur, 1994). OAs make more eye movement errors e.g. their ability to suppress undesired automated saccades is degraded (Beurskens & Bock, 2012; Butler, Zacks, & Henderson, 1999; Butler & Zacks, 2006; Harsay, Buitenweg, Wijnen, Guerreiro, & Ridderinkhof, 2010; Nieuwenhuis, Ridderinkhof, De Jong, Kok, & Van Der Molen, 2000; Olincy, Ross, Youngd, & Freedman, 1997). OAs also have longer saccadic latencies but, despite this, they show a decline in saccadic accuracy and speed (Bono et al., 1996; Moschner & Baloh, 1994; Paquette & Fung, 2011). OAs make saccades of smaller amplitudes despite similar levels of exploration as YAs during change detection tasks (Veiel, Storandt, & Abrams, 2006), visual search tasks (Plude & Doussard-Roosevelt, 1989; Scialfa, Thomas, Joffe, et al., 1994; Scialfa & Joffe, 1997), and usual field of view (UFOV) tasks (Ball & Owsley, 1991; Owsley, Ball, Sloane, Roenker, & Bruni, 1991). Furthermore, OAs spend more time looking at fewer objects (Bao & Boyle, 2009; Maltz & Shinar, 1999), and they re-fixate already inspected objects more often (Maltz & Shinar, 1999; Veiel et al., 2006). Similar findings were obtained in real-world scene exploration with OAs shifting their attention to narrower parts of the visual space with low amplitude saccades but they still showed similar levels of explorativeness to YAs overall (Açık et al., 2010).

OAs are thought to rely increasingly on top-down processes in several tasks making use of expectations regarding to-be identified items (Madden et al., 2007; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006; Whiting, Madden, Pierce, & Allen, 2005). This reliance on top-down processes may arise due to changes of bottom-up processes at a sensory level, e.g. low contrast vision, stereopsis, a reduced attentional field area (Madden, Whiting, & Huettel, 2005; Madden et al., 2007). Such declines in bottom-up processing would lead to a noisier neural signal being passed to higher cortical regions, which may require more top-down attentional control to filter and reduce the number of potential object representations (Bar &

Aminoff, 2003; Madden et al., 2007; B. A. Schneider & Pichora-Fuller, 2000). Even though OAs rely on top-down processes more strongly, this may also cause problems for OAs as top-down processes have also been shown to decline with age. Frontal regions that control top-down processes deteriorate with age (Gazzaley & D'Esposito, 2007; Kastner & Ungerleider, 2000; Salat et al., 2004). This decline in frontal lobe function has been associated with deficits in attentional control, specifically, attention being increasingly drawn by task-irrelevant stimuli (Milham et al., 2002), and a reduced ability to switch between targets (Hampshire, Gruszka, Fallon, & Owen, 2008). In terms of overt and covert attention there is conflicting evidence. While some studies show that OAs' ability to control covert attention declines (Faust & Balota, 1997; Slessor, Phillips, & Bull, 2008; Slessor, Laird, Phillips, Bull, & Filippou, 2010), others have shown that OAs are able to shift their attention covertly, but do so slower than YAs (Greenwood, Parasuraman, & Haxby, 1993).

### **Naturalistic scenes**

Many aspects of visual attentional control, such as tracking a moving object (smooth pursuit) have been shown in laboratory studies to decline in older age, but in more natural experiments these aspects of visual attentional control are maintained. For example, smooth pursuit in the laboratory has been shown to worsen in OAs as compared to YAs (Moschner & Baloh, 1994; Ross et al., 1999). Whereas visual tracking performance of a given target during self-motion (walking down a corridor) appears to be unaffected by age (Dowiasch, Marx, Einhäuser, & Bremmer, 2015). This finding might suggest that compensatory mechanisms such as head movements, or additional sensory cues like optic flow, help to maintain normal performance. It has been reported that an increased likelihood and intensity of circular vection, a psychophysical measure of visual-vestibular interactions, enhances the perception of self-motion in OAs, which might serve as a visual compensation for age-dependent loss of vestibular cues (Paige, 1994). Along similar lines, heading detection via expanding radial flow fields has been shown to be stable across the lifespan (Billino, Bremmer, & Gegenfurtner, 2008).

The majority of the findings in visual attention in ageing were yielded in well-controlled laboratory settings, where subjects sat in front of a computer display and were instructed to perform one given task. The outcome may not necessarily be replicable under situations of everyday life where persons move about, interact with an ever-changing environment, keep track of multiple concurrent tasks, produce self-initiated, complex actions and pursue ecologically valid goals rather than obeying experimenter instructions. Previous work has shown that age-related changes of manual performance (Bock & Steinberg, 2012; Bock & Züll, 2013), locomotion (Bock & Beurskens, 2010) and cognitive skills (Verhaeghen, Martin, & Sedek, 2012) are different in an everyday-like context compared to a typical laboratory context, and age-related changes of the gaze pattern may be different as well. Therefore it is important to determine whether the declines in visual attentional control still apply in everyday tasks or simulated everyday tasks.

### **1.3 Impacts on day to day activities**

Children and OAs show many difficulties in controlling visual attention, which can have a large impact on day to day activities.

#### **1.3.1 Children**

For example, children who were less able to concentrate when challenged by a distracting event tended to be more impulsive, and more impulsive children tended to cross the road in a less controlled manner (Dunbar, Hill, & Lewis, 2001). Children are more susceptible to internet advertisements, in particular, low-level saliency features of internet advertisements have a strong influence in determining children's visual attention (Holmberg, Holmqvist, & Sandberg, 2015). However, children with more voluntary or top-down control over their reflexive eye movements looked less at advertising (Holmberg et al., 2015). Children with low motor coordination ability showed impaired visuomotor control and performance in a throwing and catching task, which was related to an inability to accurately track the ball as it rebounded off the wall (M. R. Wilson, Miles, Vine, & Vickers, 2013). Gaze shifts in children

have been associated with increased body sway (Schärli, van de Langenberg, Murer, & Müller, 2012), and gaze shifts involving large head movements were associated with postural instability in children (Schärli, van de Langenberg, Murer, & Müller, 2013).

To compensate for a lack of mature perceptual-motor skills, children seem to adopt more cautious locomotor strategies, characterized by lower moving speeds and larger safety margins when an obstacle has to be avoided (Pryde, Roy, & Patla, 1997). In a study on cycling behaviour, children cycle slower than adults, and look more towards the side of the road and the surroundings, whereas adults focus more on the road itself (Vansteenkiste et al., 2017). Research has suggested that children make less use of their peripheral vision to guide actions than adults (Franchak & Adolph, 2010). The less efficient use of peripheral vision may be a reason why children looked more to the surroundings than adults (Vansteenkiste et al., 2017). Alternatively, the finding that children spent more time watching their surroundings is also in line with earlier suggestions that children have difficulties to distinguish between what is relevant and irrelevant on the road (Foot, Tolmie, Thomson, McLaren, & Whelan, 1999; Whitebread & Neilson, 2000).

### **1.3.2 Older adults**

Previous studies have linked attentional control decline in OAs to problems in day to day tasks. For example attentional control decline has been linked to motor vehicle crash rates (Shinar, Zaidel, & Paarlberg, 1978) and OAs ability to adjust their gait (Sparrow, Bradshaw, Lamoureux, & Tirosh, 2002). Older adults' decline in working memory and attention has also been linked to problems in sign acquisition during driving (Caird & Chugh, 1997; Fisk & Warr, 1998; Kidder, Park, Hertzog, & Morrell, 1997; Parasuraman & Nestor, 1991; Plude & Doussard-Roosevelt, 1989; Ponds, Brouwer, & Van Wolffelaar, 1988; Stine & Wingfield, 1990). For example when participants were presented with traffic scenes of varying clutter and luminance OAs were slower, less accurate, and required more fixations to detect traffic signs (Ho, Scialfa, Caird, & Graw, 2001). These findings suggest that OAs are more

likely than YAs to misidentify road signs or even miss signs altogether (Ho et al., 2001). Moreover, older drivers have difficulties glancing one way and navigating their vehicle in another direction (Romoser, Pollatsek, Fisher, & Williams, 2013). This would prevent OAs from being able to detect all the hazards along the road increasing the chance of a collision.

In walking, OAs look to stepping targets in the travel path sooner and fixate these targets for longer than YAs. This looking behaviour suggests that OAs need more time to process visual information describing stair locations and plan accurate stepping movements (Chapman & Hollands, 2006b; Zietz & Hollands, 2009). Other studies have demonstrated that OAs categorized as being at a high risk of falling have a tendency to look away from a stepping target prematurely and that this behaviour is associated with a reduction in the accuracy and precision of stepping movements (Chapman & Hollands, 2006b, 2007). Similar to YAs, OAs consistently look at features of the future travel path before initiating the step to the fixated location (Stanley & Hollands, 2014). However, OAs fixate obstacles and targets in the travel path for significantly longer than YAs (Chapman & Hollands, 2006a; Di Fabio, Greany, & Zampieri, 2003). The longer fixations suggest that OAs require longer to process visual information about the future travel path needed for safe locomotion (Di Fabio et al., 2003) or that they are less able to use extrafoveal information.

Attentional control, specifically the ability to inhibit task-irrelevant stimuli and the ability to switch attention between targets form parts of the family of mental processes that make up executive functions (EF). Specifically, attentional control is involved in the inhibition and cognitive flexibility components of EF (Diamond, 2013). Many aspects of EF, including inhibition, working memory, and cognitive flexibility have been shown to decline with age (for a review see Diamond, 2013). The decline in EF ability can have a large impact on day to day life, for example an age-related decline in EF has been associated with an increased driving accident rate (Anstey, Horswill, Wood, & Hatherly, 2012; G. Daigneault, Joly, & Frigon, 2002; McKnight & McKnight, 1999), a reduced ability to navigate successfully (Sangani,

Fung, Kizony, Koenig, & Weiss, 2013), and a reduced ability to maintain a stable posture (Maylor & Wing, 1996).

Another important day to day activity that involves advanced attentional control and EF ability is road crossing. An activity in which children and OAs are particularly vulnerable

## 1.4 Road crossing abilities

Pedestrians are the most vulnerable road users worldwide. More than 270,000 pedestrians die annually in road traffic crashes, constituting 22% of all road deaths (World Health Organization, 2013). Regarding child casualties, 186,300 children died from road traffic related incidents across the world in 2012, and 38% of these deaths were child pedestrians (World Health Organization, 2015). OAs (above 75y/o) have the highest rate of pedestrian accidents in (Australia Bureau of Infrastructure, Transport and Regional Economics, BITRE, 2015), and in the EU OAs make up nearly half of all pedestrian fatalities (European Road Safety Observatory, ERSO, 2018). Therefore, it is very important to analyze pedestrian behaviour and the causes of pedestrian injuries to reduce mortality rates.

### 1.4.1 Children

Research has shown that child pedestrians, especially those in the age range of 5 to 9 y/o, are highly represented in fatal and severe injury traffic crashes (National Highway Traffic Safety Administration, NHTSA, 2007; Tabibi & Pfeffer, 2003; Whitebread & Neilson, 2000), in spite of relatively low levels of exposure to traffic (Thomson et al., 2005). Traffic safety professionals suggest that children under the age of 9 or 10 should not cross the road alone (Percer, 2009). Despite this, research has shown that elementary-school children do tend to cross the road unaccompanied by adults, mainly on their way to and from school (Macpherson, Roberts, & Pless, 1998; Martin, Lee, & Lowry, 2007; McDonald, 2008; Van Der Molen, 1981). For example, through a survey of 732 elementary school parents in four urban USA neighbourhoods, it was shown that while parents tended to report that they teach

their children pedestrian safety skills, 30% of them stated that they let their child, who is younger than 10 y/o, walk to school alone (Gielen et al., 2004). Forty-seven percent of the parents stated that they did not supervise their children when playing outdoors (Gielen et al., 2004). Therefore, to reduce traffic crashes among child-pedestrians it is not enough to assume that youngsters will avoid crossing roads unaccompanied; rather, there is a need to determine the skills and knowledge required for children to deal safely with the traffic environment (Hill, Lewis, & Dunbar, 2000).

Along these lines, previous research has indicated that young children suffer from poor pedestrian skills and poor visual search strategies, as well as other perceptual and cognitive deficiencies that interfere with their ability to safely interact with the traffic environment (Ampofo-Boateng & Thomson, 1991; Barton & Morrongiello, 2011; Tomlie, McLaren, Foot, Thomson, & Whelan, 1998; Whitebread & Neilson, 2000). Recurrent observations seem to point towards specific perceptual, cognitive, and behavioural aspects involved in children's susceptibility to road traffic accidents. For instance, studies using various experimental techniques consistently showed that younger children take longer to enter a safe traffic gap than older children (judgments on videos: Pitcairn & Edlmann, 2000; cycling in virtual environment: Plumert, Kearney, & Cremer, 2004; road-crossing simulation: te Velde, van der Kamp, Barela, & Savelsbergh, 2005), which overlaps with other developing skills such as perceptual and motor abilities (Schwebel, Davis, & O'Neal, 2012). Experiments in obstacle avoidance and road crossing behaviour have shown that children younger than 10y/o adopt different visual-motor strategies than adults (Ampofo-Boateng & Thomson, 1991). Compared to adults, children look more to irrelevant areas (Whitebread & Neilson, 2000), and have more difficulties to synchronize their actions to other moving objects in road crossing situations (Connelly, Conaglen, Parsonson, & Isler, 1998). Moreover, previous studies have shown that children under 8y/o looked less often at traffic (Zeedyk, Wallace, & Spry, 2002; Zeedyk & Kelly, 2003), and when they did it was often in the opposite direction of oncoming traffic (Zeedyk et al., 2002). Eight to 10y/os monitored traffic less when vehicles were further away than

when they were closer (Morrongiello, Corbett, Milanovic, & Beer, 2015). These looking behaviours correlated with more unsafe crossing decisions in children under 8 to 10y/o (Morrongiello et al., 2015).

Even though children are initially unable to make safe crossing decisions, crossing behaviour improves with age, along with the development of their visual attentional control. For example, from 5 to 12 y/o, children become more efficient at noticing visually salient information, making decisions based on such information, and organizing appropriate actions (Thomson, Tolmie, Foot, & McLaren, 1996). Children's ability to choose a safe time to cross improves up to about 14 y/o which has been associated with an improvement in perceptual-motor functioning (Plumert, Kearney, & Cremer, 2007). In both on-road and off-road experiments, 5 to 7 y/os demonstrate poor skill in identifying dangerous road crossing sites, and their judgements rely almost entirely on the visible presence of cars in the vicinity (Ampofo-Boateng & Thomson, 1991). Nine y/os and 11 y/os, however, demonstrated the ability to make road crossing judgements correctly (Ampofo-Boateng & Thomson, 1991). When presenting traffic scenarios to 5, 7, 9, 11 y/os, and adults in three different settings – computer simulation, video technique, and roadside – older children were much more attuned to traffic-relevant features than younger children (Tomlie et al., 1998).

As discussed above the ability to cross a road safely is still developing through childhood but this development is not linear throughout the lifespan. The ability to cross the road safely also declines with age.

### **1.4.2 Older adults**

The World Health Organization (2013) reported that OAs were a more vulnerable pedestrian age group than YAs. Indeed, OAs (above 75y/o) have the highest rate of pedestrian accidents in Australia (BITRE, 2015). In the EU OAs make up nearly half of all pedestrian fatalities (ERSO, 2018). Studies on pedestrian behaviour in OAs have pointed towards deficits in motor abilities (Nagamatsu et al., 2011) and cognitive processes as factors that might explain the high number of OAs involved

in accidents. Specifically, attentional control abilities such as, attention switching (Dommes, Cavallo, & Oxley, 2013), and other EF abilities such as spatial planning have been linked to fewer safe crossing decisions (Geraghty, Holland, & Rochelle, 2016).

In terms of linking attentional control abilities with road crossing performance, OAs standing at a curbside, lower their gaze for longer time to the walkway than YAs do (Egan, 2012). Although the walkway is a useful location to look, previous studies have suggested that OAs who keep their gaze for a longer time on one given object may miss other relevant objects around them (Bock, Brustio, & Borisova, 2015; Chapman & Hollands, 2006a, 2006b; Egan, 2012). As a consequence, OAs ability to observe oncoming traffic might be compromised (Neider et al., 2011; Oxley, Ihssen, Fildes, Charlton, & Day, 2005). In a virtual reality experiment, Bock et al. (2015) found that each glance at a traffic light took longer in the older group and may reflect a generalized slowing of visual processing in OAs. It could also be a sign of OAs having problems with suppressing automated saccades towards irrelevant objects (Beurskens & Bock, 2012; Butler et al., 1999; Butler & Zacks, 2006; Harsay et al., 2010; Nieuwenhuis et al., 2000; Olincy et al., 1997). Alternatively, it has been suggested that prolonged viewing could be a compensatory strategy (Bock et al., 2015), longer glances at the traffic light may facilitate spatial orientation by minimizing eye and head movements (Zettel, Scovil, McIlroy, & Maki, 2007), and may help preparing to stop by extending the available time (Bonin-Guillaume, Possamai, Blin, & Hasbroucq, 2000; Roggeveen, Prime, & Ward, 2007). However, prolonged viewing might also cause problems as OAs who keep their gaze on the traffic light might miss other important events in their environment such as cars or cyclists coming down the road (Bock et al., 2015). Zito et al. (2015) linked visual sampling, EFs, and road crossing decisions with age. They showed that although both OAs and YAs look mostly at the appearing point of the vehicles, OAs spend more time than YAs looking at the ground in front of them. Moreover, OAs made more unsafe crossing decisions and showed a decline in EF. In line with this, OAs have been found to look directly in front of them more before and during a virtual

road crossing, compared to looking at the periphery, where the cars enter the road (Tapiro, Borowsky, Oron-Gilad, & Parmet, 2016). This could be problematic for OAs as it might not give them enough time to determine the speed of the vehicles, and they may miss additional hazards other than cars.

## 1.5 Rationale and scope of thesis

In summary, the previous literature points to children and OAs having deficits in their visual attentional control abilities which affects large aspects of their day to day life such as walking, playing sports, and crossing the road. Previous studies investigated perceptual processes in road crossing situations used very general descriptions of the children or OAs looking towards or away from the traffic during simulated and real crosswalks (Barton & Schwebel, 2007; Zeedyk & Kelly, 2003). Similarly, studies using virtual reality to investigate perceptual processes in road crossing scenes have only reported head movements following the traffic (Morrongiello et al., 2015) or between computer screens (Whitebread & Neilson, 2000), rather than a detailed description of how children and OAs explore the visual field compared to YAs. To our knowledge, no studies have provided a fine-grained description of how exactly children and OAs explore the visual field compared to YAs, and how these explorations affect road crossing decisions. Tapiro, Meir, Parmet, and Oron-Gilad (2014) and Tapiro et al. (2016) conducted a more fine-grained analysis of visual attention of YAs, children, and OAs in road crossing situations. Children and OAs looked preferentially at areas in front of them, while YAs looked preferentially at more distant locations. Along with this, Zito et al. (2015) linked visual sampling, EFs, and road crossing decisions with age. Both Tapiro et al. (2014) and Zito et al. (2015) did not analyse if there was a direct link between gaze behaviour, EF ability, and unsafe crossing decisions. It therefore remains unclear whether EF abilities influence crossing decisions and gaze behaviour in a road crossing scenario. Moreover, the gaze analyses relied on areas of interest (AOIs) based on a-priori segmentation of the stimulus space, preventing the data driven discovery of meaningful patterns (see Caldara & Miellet, 2011 and Miellet, Lao, & Caldara, 2014 for a discussion of

the limitations of AOIs). Critically, to our knowledge, there are no studies in the literature that have used naturalistic scenes and directly investigated the link between executive control, perceptual processes, and road crossing behaviour of children, YAs, and OAs.

In this thesis I propose to determine how attentional control changes, during the developmental and ageing processes, how these changes in attentional control affect information sampling, and behaviour in children, YAs, and OAs. The present thesis aims to determine whether there is a critical age at which children show similar attentional control skills and behavioural performance to YAs, and how these skills start to decline during ageing, in a naturalistic, dynamic, and socially relevant task: road crossing. To achieve these aims a variety of methods ranging from eye-tracking to image processing, EEG, and VR were used, and new techniques tailored to the questions at hand were developed. I created two road crossing tasks and a multiple object tracking EEG task which all require advanced attentional control skills. The first road crossing task that I created involved 5 to 15y/o children (Chapter 2), YAs, and OAs (Chapter 3) watching road crossing videos, and indicating with a key press when the participant thought it was safe to cross. I recorded their eye movements while participants performed the task. The second road crossing task (Chapter 4) involved a virtual road crossing environment presented across multiple screens which allowed us complete control over the environment while maintaining a high level of realism. The virtual environment allowed us to assess participants' road crossing performance across multiple situations involving multiple lanes, varying car speeds, directions, traffic density and pedestrian distractors. The participants' attentional control abilities through eye tracking across a large field of view was also investigated. The combined EEG and eye tracking paradigm involved tracking single and multiple objects (Chapter 5). The use of EEG allowed us to differentiate between covert and overt attention while tracking moving objects, and is the first to investigate the steady-state evoked potential (SSVEP) during smooth pursuit. This experiment may have implications for future road crossing and attentional control research.

# Chapter 2

## Developing attentional control in naturalistic dynamic road crossing situations

This chapter has been published as: Nicholls, V. I., Jean-Charles, G., Lao, J., de Lissa, P., Caldara, R., & Mielle, S. (2019). Developing attentional control in naturalistic dynamic road crossing situations. *Scientific Reports*, *9(1)*, 1-10. <https://doi.org/10.1038/s41598-019-39737-7>

### 2.1 Introduction

Human visually guided behaviour relies on the selective uptake of information, due to sensory and cognitive limitations (Ludwig, Davies, & Eckstein, 2014). In other words, human vision is a dynamic process, during which the observer actively samples the environment in order to gather diagnostic information for the task at hand. This is made possible by our attentional systems selecting information based on bottom-up stimulation (Borji et al., 2013; Bruce & Tsotsos, 2006, 2009; Itti & Koch, 2001; Marat et al., 2009) and top-down influences (Henderson et al., 1999; Loftus & Mackworth, 1978; S. E. Palmer, 1975; Tatler et al., 2011; Wolfe et al., 2011).

The focus on top-down processes has been of increasing interest in the last 20

years, as the study of visual processing has sought to involve more natural conditions and realistic stimuli. Many recent studies used photographs and included eye movement recordings to look at the influence of context on visual attention (Eckstein et al., 2006; Henderson, Chanceaux, & Smith, 2009; Henderson, Malcolm, & Schandl, 2009; Malcolm & Henderson, 2010; Vö & Henderson, 2010; Wolfe et al., 2011). For instance, these studies have shown influences of semantic (A. D. Hwang et al., 2011), episodic top-down processes (Castelhana & Henderson, 2007; Castelhana & Heaven, 2011; Vö & Wolfe, 2012), as well as scene context on parafoveal processing of objects (Castelhana & Pereira, 2018; Pereira & Castelhana, 2014). More recently, the role of the observer's intention and understanding of the scene has been emphasized (Hayes & Henderson, 2017; Henderson, 2017). In this perspective, oculomotor planning is seen as making predictions about the locations of diagnostic information for the task (Friston et al., 2012).

These top-down processes are generally considered as being mainly under control of the frontal regions, which are still maturing during childhood (Booth et al., 2003; Bunge et al., 2002; Durston et al., 2002; K. Hwang et al., 2010; Kastner & Ungerleider, 2000; Konrad et al., 2005). This protracted maturation of the frontal lobes has been associated with a lack of top-down attentional control (Colombo, 2001) and a deficit of top-down inhibition of reflexive, automatic saccades (Munoz & Everling, 2004; Paus, 1989). This is consistent with research showing more express saccades, a slower pro- and anti-saccade reaction time and a higher error rate in the anti-saccade tasks for children compared to adults (Fukushima et al., 2000; Klein et al., 2000; Klein & Foerster, 2001; Munoz et al., 1998). In terms of critical age, Leclercq and Siéroff (2013) suggested that 6 and 8 (y/o) year old children fail to inhibit attentional capture by goal irrelevant stimuli while 10 y/os and adults succeed. Klein et al. (2000); Klein and Foerster (2001) showed that adults exhibited faster saccades and fewer prosaccades during the anti-saccade task than 10–11 y/os, who in turn had faster saccades and fewer prosaccades than 6 and 7 y/os. Additionally, Munoz et al. (1998) showed that children between 5 and 8 y/o had slow saccadic reaction times (SRTs) and the most direction errors in the anti-saccade task, which is re-

lated to the protracted maturation of the frontal lobes (Munoz & Everling, 2004). These studies suggest that children between 8 and 10 y/o have similar attentional control skills to adults. However, it is important to mention that most of these studies used basic situations involving only flashing of very simple target stimuli. As explained above, more naturalistic situations and stimuli involve top-down processes more strongly. Thus, it is possible that the complexity and realism of the task influences the critical age at which children show stronger oculomotor capture and decreased inhibition of responses to task irrelevant distractors compared to adults. Using static natural images, Aık et al. (2010) found that children under the age of 10 use oculomotor strategies particularly influenced by bottom-up processes. These authors tested children from 7–9 y/o, adults from 19–27 y/o, and older adults above 72 years of age. More recently, Kuhn and Teszka (2017) explored differences in attentional control between adults and children within a more natural context. Their results suggest that children below the age of 10 are more distracted than adults and this influences how they experience the world around them.

In the present study, we propose to determine the trajectory of the difference in attentional control, its effect on information sampling, and behaviour between children and adults. Moreover, the present study aims to determine whether there is a critical age at which children show similar attentional control skills and behavioural performance to adults, in a naturalistic, dynamic, and socially relevant task. To these aims, we created a road crossing task which requires advanced attentional skills. Crucially, besides addressing an important theoretical question, the present study aims to shed light on a critical practical issue associated with road safety. Road traffic accidents killed 273,000 pedestrians worldwide in 2010 – 22% of all road traffic accidents that year (World Health Organization, 2013). Regarding child casualties, 186,300 children died from road traffic related incidents across the world in 2012, and 38% of these deaths were child pedestrians (World Health Organization, 2015). Recurrent observations seem to point towards specific perceptual, cognitive, and behavioural aspects involved in children’s susceptibility to road traffic accidents. For instance, studies using various experimental techniques

consistently showed that younger children take longer to enter a safe traffic gap than do older children (judgements on videos: Pitcairn & Edlmann, 2000, cycling in a virtual environment: Plumert et al., 2004, and a road crossing simulation: te Velde et al., 2005), which overlaps with other developing skills such as perceptual and motor abilities (Schwebel et al., 2012). Previous studies investigating the effect of perceptual processes on road crossing performance reported that children aged under 8 y/o looked less often at traffic (Zeedyk et al., 2002; Zeedyk & Kelly, 2003), and when they did it was often in the opposite direction of oncoming traffic (Zeedyk et al., 2002). 8–10 y/os monitored traffic less when vehicles were further away than when they were closer (Morrongiello et al., 2015). These looking behaviours were correlated with children under 8–10 y/o making more unsafe crossing decisions.

However, these studies investigated perceptual processes using very general descriptions of the children looking towards or away from the traffic during simulated and real crosswalks (Barton & Schwebel, 2007; Zeedyk & Kelly, 2003). Similarly, studies using virtual reality (VR) reported head movements following the traffic (Morrongiello et al., 2015) or between computer screens, as well as duration looking at a computer screen (Whitebread & Neilson, 2000). None of these studies, however, provide us with a fine-grained description of how exactly children explore the visual field compared to adults, and how these explorations affect road crossing decisions. Tapiro et al. (2014) conducted a more fine-grained analysis of visual attention of adults and children in road crossing situations. Children looked preferentially at areas in front of them, while adults looked preferentially at more distant locations. However, the analysis relies on areas of interest (AOIs) based on a-priori segmentation of the stimulus space, preventing the data driven discovery of meaningful patterns (see Caldara & Miellet, 2011 for a discussion on the limitations of AOIs). Critically, to the best of our knowledge, there is no study in the literature that includes distractors and their effects on visual exploration as a way to investigate attention switching and inhibitory control, and how these develop in children for real world scenarios.

The current study aimed to isolate the critical age at which road crossing deci-

sions and oculomotor patterns of children differ from those of adults. We wanted to characterise precisely children’s visual processing specificities and explore the impact of distractors and task complexity. Based on the psychophysics and the road safety literatures our main hypothesis was that children under 10 y/o, for whom studies have shown a reduced inhibitory control attributed to protracted maturation of the frontal lobes (Munoz & Everling, 2004) and fewer safe crossing decisions, would produce an increased number of saccades towards task irrelevant stimuli which would, in turn, impact negatively on optimal information sampling for road crossing decisions. We therefore presented child participants aged 5 to 15 (and adult controls) with videos of naturalistic road crossing scenarios. Participants were then asked to decide when to initiate a road crossing and to keep pressing the key as long as the crossing was possible. We included varying levels of traffic density to investigate how this factor influences task difficulty and attention switching, and thus crossing and eye movement behaviours. Additionally, we included pedestrians as they are known to be a potent distractors for attentional capture, in order to test for inhibitory control.

## 2.2 Methods

All data is publicly available via the Open Science Framework through this DOI:

DOI 10.17605/OSF.IO/B3YPC

### 2.2.1 Participants

67 participants were recruited: 57 aged between five and 15, and 10 adult controls aged between 20 and 40 (mean=24, SD=3). All children were recruited in schools in the Fribourg canton, Switzerland. Adults were recruited from the University of Fribourg. All participants had normal or corrected to normal vision. The study was approved by the Department of Psychology ethics committee at the University of Fribourg. Informed consent was obtained from the schools, parents, children, and adult controls prior to taking part in the study. This study was performed in accordance with all appropriate institutional and international guidelines and

regulations, in line with the principles of the Declaration of Helsinki.

### **2.2.2 Apparatus**

During the experiment participants' eye movements were recorded at a sampling rate of 1000Hz with the SR-Research EyeLink 1000 (with a chin and forehead rest), which has an average gaze position error of  $0.25^\circ$ , a spatial resolution of  $0.01^\circ$ , and a linear output range over the range of the monitor used. Only the dominant eye was tracked. Stimuli were presented on an HP monitor with a screen resolution of 1920 by 1080 pixels, a width of 521mm and a height of 293mm, a horizontal viewing angle of  $46.9^\circ$  and a vertical viewing angle of  $27.4^\circ$  at a distance of 600mm. The experiment was coded in Matlab (MATLAB, 2016) using Psychophysics (PTB-3) and EyeLink Toolbox extensions (Brainard, 1997; Cornelissen, Peters, & Palmer, 2002). Calibrations for eye fixations were conducted at the beginning of the experiment using a nine-point fixation procedure as implemented in the EyeLink API (see EyeLink Manual) and using Matlab software. Calibrations were then validated with EyeLink software and repeated until the optimal calibration criterion was reached.

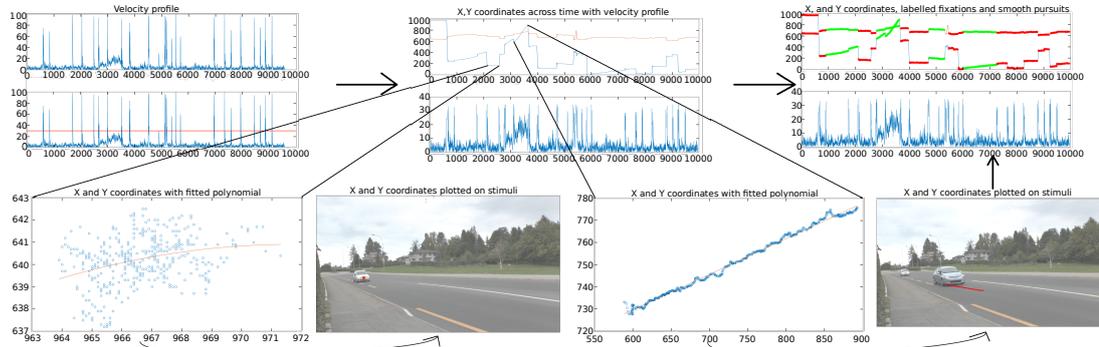
### **2.2.3 Experimental Design**

At the beginning of the experiment participants were informed that they would be presented with a series of videos of road crossing situations on screen and that they would have to indicate by pressing the spacebar on a keyboard when they could cross the road and hold the button pressed for as long as they thought it was safe to cross. Participants were instructed to focus on approaching vehicles on the side of the road closest to them (see Figure 2.1a for a capture of the scene). Vehicles travelled at an average velocity of 50 km/h. Each trial started with the presentation of a central fixation cross. Once the participants had fixated on the cross a blank screen was presented for 500 ms and then the video clip for the trial was presented (see Figure 2.1a). Each trial was followed by another blank screen for 500 ms and the next trial started with the central cross. 100 trials were presented to the participants each with a different video clip, each lasting 10 seconds. All video clips were filmed at

a real road crossing in Fribourg with a variety of traffic densities, with or without pedestrians and cyclists (distractors). Number of presses for each trial were collected and analysed for the purpose of the present experiment.



(a) Example video stimuli



(b) Illustration of eye parser algorithm

Figure 2.1: Example video stimuli and illustration of eye parser algorithm (a) A screenshot taken from the a video clip shown during a single trial of the experiment. The videos are filmed at an angle, so the participants can see the approach of vehicles only from one side of the road. (b) Top left – velocity threshold to extract saccades (bottom panel). Velocity of eye movement samples (top panel). Top centre – plotting X and Y coordinates of eye movement samples across whole trial (top panel). Bottom left and right – extraction of segments of eye movement samples maintaining a velocity of 30 deg/s for at least 100 ms with a polynomial fitted to the segments. Beside these are X and Y coordinates of the segments plotted on matching frames of the experiment stimuli. Top right – completed labelling of eye movements as fixations (red lines), smooth pursuits (green lines), and saccades (blue lines) for a whole trial.

## 2.2.4 Statistical Analyses

All statistical analyses and figures were performed and created using Matlab 2016a (MATLAB, 2016) and R (R Core Team, 2016) with RStudio (RStudio Team, 2016).

The literature suggests that crossing decisions are different below and above 10 years old. We corroborated this critical age, in a data-driven way to avoid confirmation bias, using a k-means clustering on the mean number of crossing decisions

per participant (Figure 2.4a). We used the Matlab k-means function, based on the k-means++ algorithm, and ran 1000 iterations to verify that the centroids were grouping consistently. The k-means procedure isolated the following clusters: 5-10y/os (mean=8, SD=1) and 11-15y/os (mean=13, SD=1). The number of and duration of button presses were analysed using a Yuen’s test with 20% trimmed means in R using the WRS2 package (Mair & Wilcox, 2018). Eye movements were parsed into fixations, saccades, and smooth pursuits using a custom algorithm. Saccades were extracted using the same parameters as the EyeLink software (a velocity threshold = 50°/s). If the majority of samples in the trial were above this threshold then the trial was removed and if more than 50% of the trials were removed then the participant was excluded. In total, 31 trials were removed, and five participants were excluded for noisy recording. Potential smooth pursuit segments were first isolated as segments for which velocity was maintained below or equal to 30°/s for a minimum of 100ms. From this initial extraction, smooth pursuit segments were identified using a dispersion threshold, based on the following algorithm. A polynomial was fitted to the X and Y coordinates of the gaze samples in each smooth eye movement segment, after having removed outliers using the Corr v2 toolbox (Pernet, Wilcox, & Rousselet, 2013). The root-mean square error of the polynomial fit was then calculated and divided by the exponential of the arc length (calculated using the arclength toolbox, D’Errico, 2010) of the polynomial. A threshold was set at  $1 \times 10^{-9}$  and samples below that threshold were considered as smooth pursuit, while samples above were considered as part of a fixation. This algorithm is summarized in Figure 2.1b and the following equation:

$$P_{RMSE} / \exp(A)$$

$P_{RMSE}$  is the root mean square error of the polynomial line,  $A$  is the arc length of the polynomial line. For each video clip the presence of a human distractor was encoded in a dichotomous way (1 for one or more human distractors present in the trial, 0 for no human distractors in the trial). The number of vehicles on each trial (traffic density) was determined using Matlab’s computer vision toolbox (MATLAB,

2016a). This toolbox uses a background subtraction algorithm involving Gaussian mixture models to detect the foreground of each frame of the video. This is followed by a blob analysis to detect and count moving objects – the vehicles in the trial videos (for an example see Kingdom, 2017).

Oculomotor characteristics were analysed using shift functions that were run in R using code from (Rousselet, Pernet, & Wilcox, 2017). The oculomotor characteristics included fixation, pursuit and saccade durations, number, and proportion of trial time. The shift functions were produced for the 9 oculomotor characteristics according to age group, presence of human distractors, and traffic density. High and low traffic density categories were produced using a kernel density plot of the number of cars on each trial (Figure A.1 in Appendix A). The centre of the distribution of car traffic density was found to be three cars present in the trial. Gaze samples were further analysed using gaze similarity matrices (GSMs). GSMs were computed by creating, for each participant and each trial, smoothed ( $1^\circ$  of visual angle) Z-scored maps of the gaze positions as in Lao, Mielle, Pernet, Sokhn, and Caldara (2017). The Fisher transformed correlations of the gaze map on a single trial with the gaze maps for all other trials were calculated for each participant individually (Figure 2.2a-c). Finally, the mean similarity between the gaze map on a single trial and all the other maps were computed for each participant, leading to 100 values per participant that were used to compute the age group with bootstrapped confidence intervals (Figure 2.2d).

Statistical maps were calculated with the iMap toolbox, version 4 (Lao et al., 2017). iMap computes pixel-wise linear mixed models (LMMs) across participants and trials on each z-score map. iMap uses a universal bootstrap clustering test to resolve biases in parameter estimation and problems arising from multiple comparisons (Pernet, Chauveau, Gaspar, & Rousselet, 2011; Pernet, Latinus, Nichols, & Rousselet, 2015). The LMM included pedestrian presence, traffic density, and age group as fixed effects. The model also included random intercepts for subject and video stimuli. Initially the model included random slopes of age group, pedestrian presence, and traffic density for each random intercept; however, this initial model

did not converge so all random slopes were removed.

## 2.3 Results

### 2.3.1 Eye Movement Results

#### Global characteristics

General oculomotor characteristics were within a similar range for each age group (see Table 2.1). Critically, all age groups showed an impact of pedestrians on their global oculomotor characteristics, while only 5–10 y/os showed an impact of traffic density. There was an overall trend for the number of fixations for 5–10 and 11–15 y/os to increase when pedestrians were present in the scene. Adults and 11–15 y/os showed an overall trend to decrease their number of pursuits. All groups showed an overall trend of increasing trial time as fixation when pedestrians were present. Additionally, 11–15 y/os and adults showed an overall trend of decreasing total trial time as pursuit when pedestrians were present. Finally, 5–10 y/os showed an overall trend of decreasing the number of pursuits with lower traffic density. Supplementary Figures A.2–A.19 and summary A.2 in Appendix A provide a detailed description of subtle differences in the distributions at the decile level.

Table 2.1: General oculomotor characteristics. The mean number of and proportion of trial time as each eye movement type. Square brackets contain 95% confidence intervals.

<i>Global characteristics</i>	<i>5-10y/o</i>	<i>11-15y/o</i>	<i>Adults</i>
<b><i>Fixations</i></b>			
Number of	19.15 [18.95,19.35]	20.89 [20.68,21.11]	21.92 [21.58,22.26]
Trial time as (ms)	3319.84 [3261,3379]	3635.79 [3578,3694]	3535.11 [3332,3528]
<b><i>Smooth pursuits</i></b>			
Number of	8.79 [8.65,8.93]	9.29 [9.15,9.43]	10.38 [10.11,10.64]
Trial time as (ms)	4738.25 [4667,4809]	5043.59 [4977,5110]	5164.51 [5048,5282]
<b><i>Saccades</i></b>			
Number of	41.61 [40.40,42.80]	39.11 [38.52,39.69]	45.02 [43.65,46.40]
Trial time as (ms)	906.26 [888.3,924.4]	814.48 [802.6,826.5]	850.119 [829.3, 870.9]

#### Gaze Similarity

In addition to looking at global eye movement characteristics, we investigated the variability in gaze patterns across the trials and age groups through gaze similarity

matrices (GSMs). GSMs are based on pairwise correlations between the trials' smoothed gaze maps. Thus, GSMs reveal the variability or consistency in gaze locations through the experiment (across trials). Figure 2.2d shows, for each of the 100 trials, the average correlation between its gaze map and the gaze maps generated by the other 99 trials. The trials are sorted according to how consistent their gaze map is compared to all the other trials. The shaded areas represent bootstrap confidence intervals across participants. Figure 2.2a–c suggests that 5–10 y/os have the least consistency in gaze behaviours across trials, while adults are the most consistent. This is illustrated most clearly by Figure 2.2d which shows that 5–10 y/os produce significantly less consistent gaze patterns across trials compared to 11–15 y/os, and adults, who do not differ from each other.

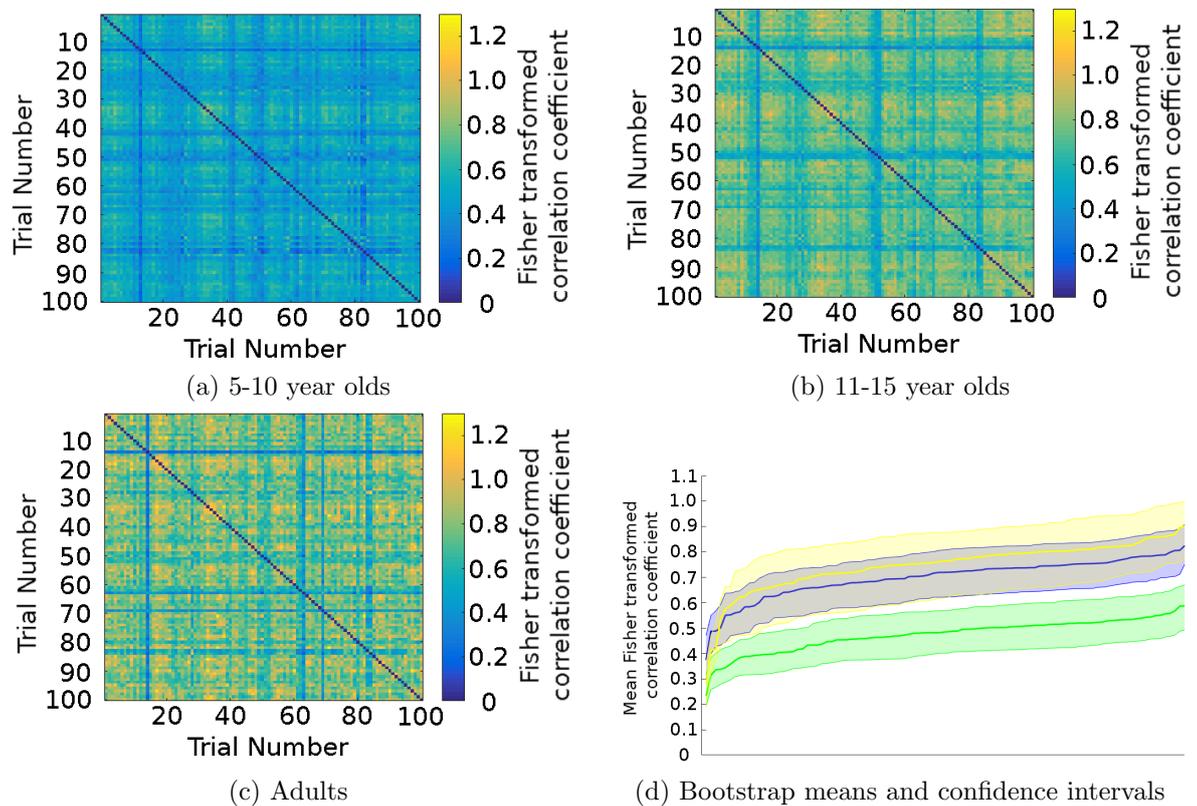


Figure 2.2: Gaze similarity figures. Panels (a–c) are mean GSMs for each group. Panel (d) is the mean Fisher transformed correlation coefficient, with bootstrap confidence intervals for each trial, sorted by highest value. Data in yellow are from adults, blue from the 11–15 y/o group, and green from the 5–10 y/o group.

## Statistical Mapping

Statistical mapping using iMap4 (Lao et al., 2017) allowed us to spatially isolate the effect of age on gaze pattern. Moreover, we explored how distractors and task difficulty specifically impact on gaze distribution across ages.

iMap analysis revealed that age group impacted on the favoured gaze location on the videos. The statistical map for the main effect of age (Figure 2.3a) shows significant differences at the beginning of the vehicle’s trajectory and the sidewalks. This age effect can be characterised by representing the differential gaze distributions for each age group. More precisely, older participants maintain their gaze within a smaller area (Figure 2.3d–f) – adults gaze mainly at the beginning of the vehicle’s trajectory while 11–15 and 5–10 y/os progressively show a wider gaze distribution covering the sidewalks and a larger proportion of the road (significant areas 2830, 3409 and 4183 pixels for adults, 11–15 y/os and 5–10 y/os respectively). Figure 2.3g–i illustrates this by representing pairwise contrast between all age groups, depicting statistical differences in gaze distributions across age groups.

The interaction between age group and pedestrian presence (Figure 2.3b) reveals a significant area over the sidewalks. The interaction between age group and traffic density (Figure 2.3c) shows a significant area on the part of the road corresponding to approaching vehicles. These significant interactions were investigated further via simple effects of pedestrian presence and traffic density for each age group (Figure 2.3j,k). The effect of pedestrian presence and traffic density were only significant for 5–10 y/os (Figure 2.3j). When a pedestrian was present in the videos, 5–10 y/o children looked more at the sidewalks (Figure 2.3k) which was not the case for 11–15 y/os and adults. When the traffic was dense (more than 3 vehicles on screen) 5–10 y/o children looked further down the vehicle’s trajectory (compared to the maximum of their gaze distribution, at the appearing point). Such an effect was not observed for 11–15 y/os and adults

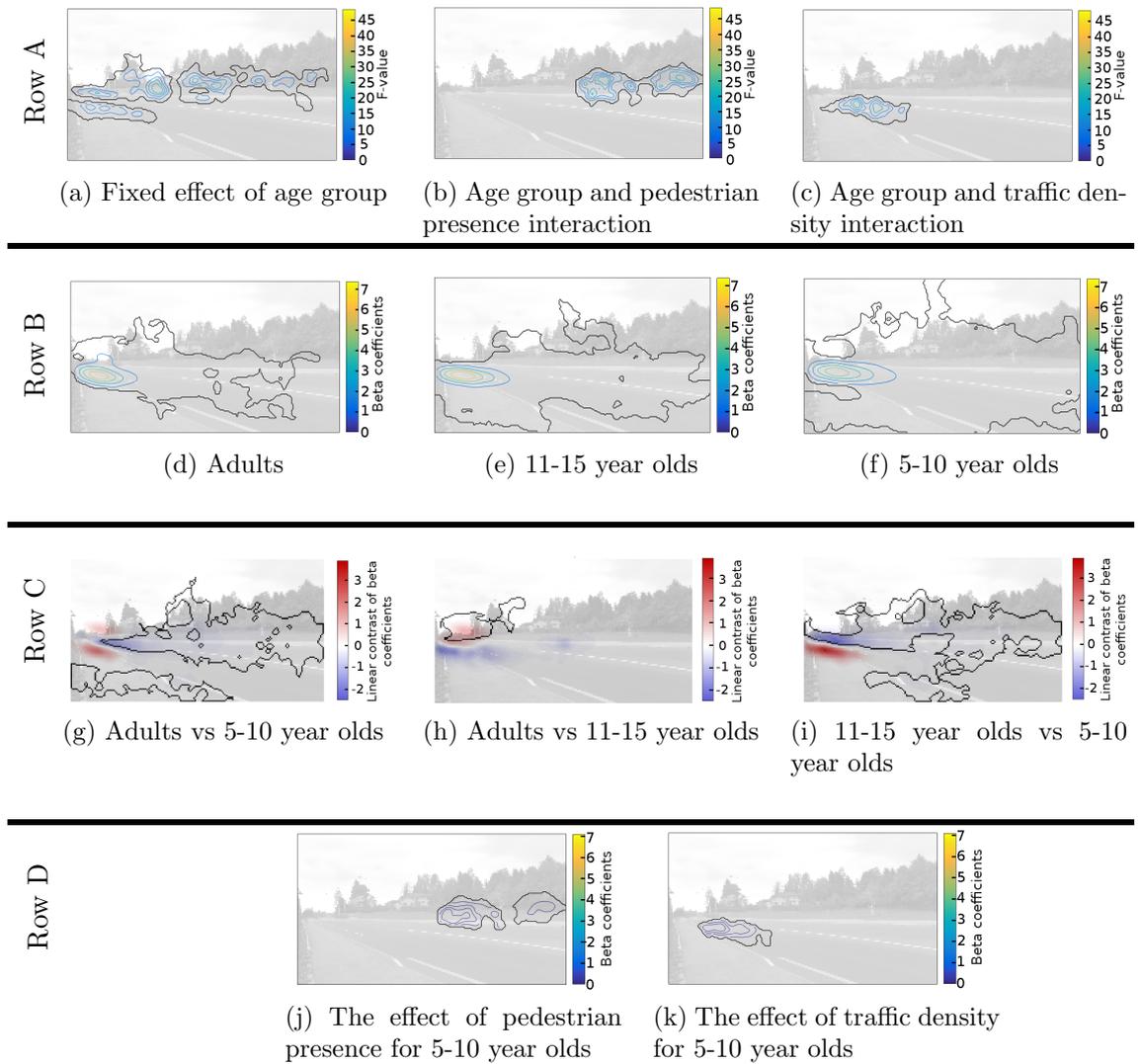
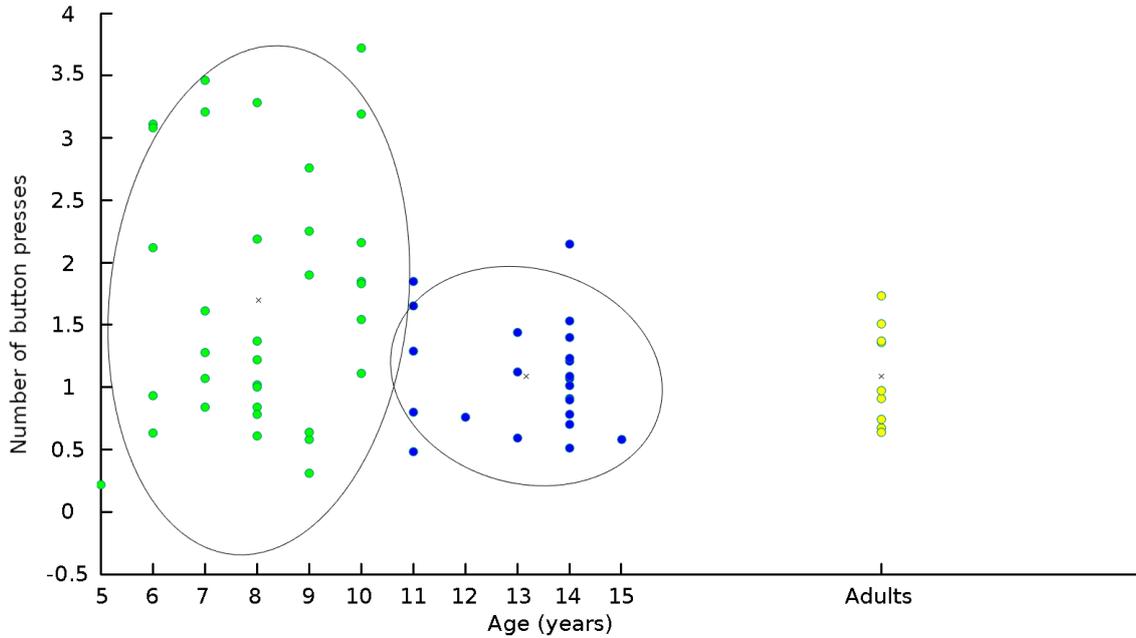


Figure 2.3: iMap4 analysis. (A) Statistical gaze maps with colour coding indicating the F-values. (B) Beta maps for each age group. (C) Pairwise contrasts between each age group. Warm colours indicate areas where the older age group looked more, compared to the younger age group. (D) Effect of pedestrian presence and traffic density for 5–10 y/os.

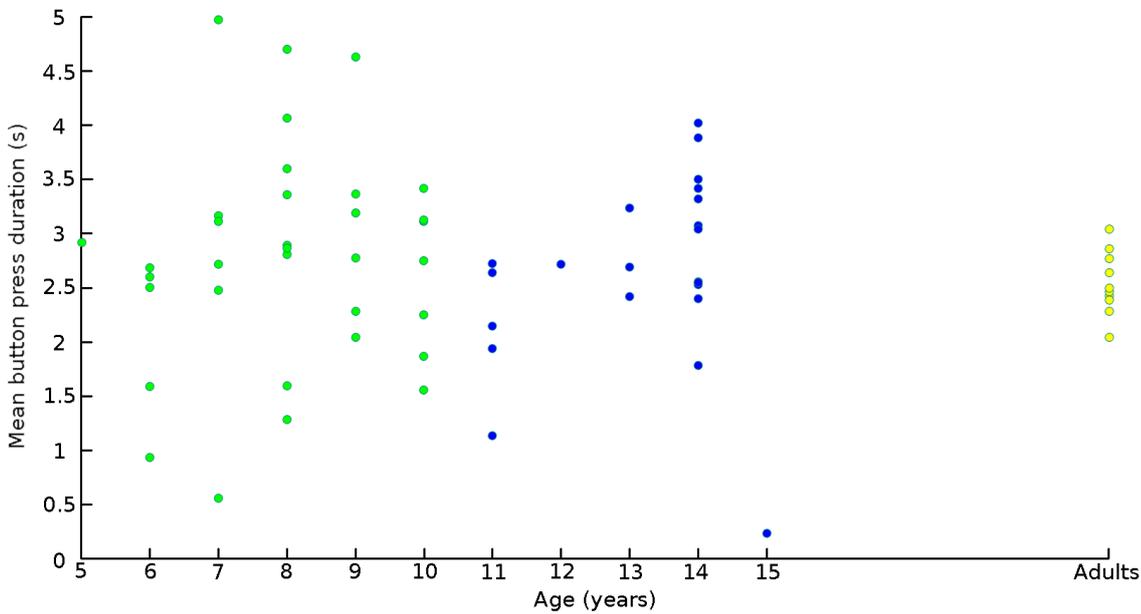
### 2.3.2 Road-crossing decisions

A k-means analysis on the mean number of crossing decisions per participant corroborated differences in performance for children below and above 11 y/o. Indeed, the k-means procedure isolated the following clusters: 5-10 y/os (mean=8, SD=1) and 11-15 y/os (mean=13, SD=1). The Yuen’s test showed 5-10 y/os made significantly more button presses than 11-15 y/os ( $t=10.70$ ,  $df=3414$ ,  $p<0.05$ ,  $d=0.29$ , see Figure 2.4a) and adults ( $t=9.86$ ,  $df=2410$ ,  $p<0.05$ ,  $d=0.25$ ). Contrastingly, 11-15 y/os

do not differ from adults in the number button presses ( $t=1.27, df=1755, p=0.20, d=-0.043$ ). The Yuen's test showed 5-10 y/os pressed for longer than adults ( $t=8.42, df=1650.77, p<0.05, d=0.25$ ; see Figure 2.4b) and 11-15 y/os ( $t=8.25, df=3361.33, p<0.05, d=0.23$ ). 11-15 y/os did not press differently from adults ( $t=0.876, df=1440.98, p=0.38, d=0.03$ ).



(a) Number of button presses



(b) Button press duration

Figure 2.4: The mean number of crossing decisions (a) and mean button press durations (b) per trial for individual participants. Each figure is a scatter plot with coloured dots indicating the different groups determined by k-means clustering. The yellow scatter points are the adult group data, blue represent 11–15 y/os, and green are 5–10 y/os. The ellipses highlight the clusters identified by k means (button press number only).

## 2.4 Discussion

We recorded eye movements of adults and children while they watched videos of road traffic and were asked to decide when they believed they could cross the road. Eye movement data showed that 5–10 y/os exhibited a much less systematic gaze scanpath than older children or adults. Indeed, older children and adults mainly looked at the beginning of the vehicle’s trajectory. In contrast, younger children showed sparse gaze distributions, covering sidewalks and the vehicle’s trajectory closer to them. All age groups showed disruptions in general oculomotor characteristics depending on the presence of pedestrians in the scene. However, only younger children showed direct gazing at the areas with pedestrian distractors. The traffic density had an effect on younger children’s general oculomotor characteristics, with more fixations in locations closer to the observer. The crossing decision results are consistent with previous literature (Connelly et al., 1998; Lee, Young, & McLaughlin, 1984), and confirm a critical age of 10, under which children made more crossing decisions.

The higher number of road crossing decisions for 5–10 y/os compared to adults and older children were associated with gaze pattern biases. The young children’s gaze patterns were characterised by less consistency across trials and more spread across the stimulus space. More specifically, younger children looked significantly more at the sidewalk area than adults and older children when human beings were present in the scene. This suggests that human beings attract the overt attention of younger children but not of older children and adults. Interestingly, human beings in the scene disrupted general oculomotor measures (more fixations, fewer pursuits, smaller proportion of trial as pursuit, and larger proportion of trial as fixation) for all age groups. Hence, it seems that socially relevant stimuli (including faces, body motion, etc.) capture the covert attention of all age groups but that only younger children direct their gaze towards this type of stimuli, which are irrelevant to the crossing task. It is possible that older children and adults are able to inhibit saccades towards irrelevant stimuli, while younger children are lacking the inhibitory control to do so. This scenario is consistent with the findings of psychophysical

and neuroscientific studies that children are less able to inhibit automatic saccades, instead directing their overt attention towards task irrelevant stimuli, which is linked in the literature to the ongoing maturation of executive functions due to a protracted maturation of frontal lobes (Munoz & Everling, 2004; Paus, 1989).

In all traffic density situations, adults and 11–15 y/os look at the top-left of the road in our paradigm – the appearing point of the cars. We propose that the reason this strategy is used is that this location represents an ideal fixation position for assessing the vehicle’s speed and time to impact as early as possible. Moreover, this gaze location allows the pedestrians to monitor for new vehicles entering the lane, thus to detect gaps, or end of gaps, very early. As the vehicles approach closer to the pedestrians, they could easily be tracked using peripheral vision as their retinal projection gets larger. Children aged between 5 and 10 also appear to be able to use this strategy, as their gaze is also focused on the appearing point of the car. However, in high traffic density situations, children look at the appearing point, as well as further down the road. We suggest that this is because they are following the cars down the road with their gaze, rather than just gazing at the appearing point. This may be due to an inability of 5–10 y/os to disengage their attention from task irrelevant stimuli, once their attention has been drawn by them. This hypothesis is consistent with studies showing that individuals in general are drawn to stimuli before disengaging to focus their attention on the target stimuli (M.-S. Kim & Cave, 1999; Theeuwes, Atchley, & Kramer, 2000). While pursuing the vehicles, the observers’ attention is focused on the vehicle moving down the road and is not be able to attend to other vehicles entering the road. This scenario is in line with studies showing that participants are not able to allocate much attention to objects in the periphery while pursuing a target (Hutton & Tegally, 2005; Lovejoy, Fowler, & Krauzlis, 2009). Without accurate information about vehicle position children would not be able to make informed crossing decisions which could lead them to cross unsafely.

Overall, our results show systematic links between eye movement patterns and road crossing decisions across development. We propose that gaze locations have a

direct impact on crossing decisions. Children orient their overt attention towards human distractors more than 11–15 y/os and adults. This tendency would impair their ability to attend to the vehicles, thus making accurate judgements about a vehicle’s distance more difficult.

Our study provides new important insights in children’s deficits in attentional control in realistic situations, particularly their vulnerability as pedestrians. Our findings are consistent with recent studies that show a very similar pattern of development. In real life situations, Connelly et al. (1998) demonstrated that children below 11 years of age do not make safe decisions. Simpson, Johnston, and Richardson (2003) reach similar conclusions using a VR head mounted display. Some recent studies used immersive VR environments allowing for realistic pedestrian (O’Neal et al., 2017) or cyclist actions (Chihak et al., 2010; Grechkin, Chihak, Cremer, Kearney, & Plumert, 2013), and unveiled the developmental trajectory of the fine-tuning between perception, decision, and action.

This study isolated, for the range of situations tested, the critical age from which children’s attentional control is at adult level in a road crossing task. Children below 11 years of age show differences in their visual explorations, characterised by a more spread gaze distribution, more overt attention to stimuli irrelevant to the task, and more gazing following the vehicles closer to the participant. This specific oculomotor pattern was associated with riskier crossing decisions in shorter traffic gaps compared to older children and adults. Our findings suggest that below 11 years of age, children do not employ attentional control to a level required for safe crossing decisions. Thus, training and education programs might specifically target these vulnerable children and their caregivers. It is also important to note that our task incorporated only one traffic direction. Thus, the critical age might occur even later in more complex and taxing situations incorporating two traffic directions.

This work helps us to better understand general deficits in children’s attentional control in real world situations, and in particular their vulnerability as pedestrians. In future studies, these initial findings will be supplemented by ongoing research investigating questions such as the visual exploration in 3D, fine-grained analyses

of time to impact and moment by moment crossing decisions, the mechanisms of attentional disengagement, the neural correlates of visuo-attentional processes for children as pedestrians, and large fields of view with two traffic directions involving eye and head movement coordination.

# Chapter 3

## Ageing with maintained executive functioning abilities is associated with effective compensatory strategies in dynamic perceptual decisions

### 3.1 Introduction

Attentional control, the ability to limit information processing to that relevant for the task, is crucial to effective functioning in daily life. Attentional control declines with age (Lustig & Jantz, 2015; Treitz, Heyder, & Daum, 2007) and this decline has been linked to the deterioration of the prefrontal cortex with age (Fjell, McEvoy, Holland, Dale, & Walhovd, 2013; Raz et al., 1997, 2005; Salat et al., 2004; West, 1996, 2000) as well as micro- and macrostructural alterations in brain connectivity between the frontal areas and other parts of the brain (Fjell, Sneve, Grydeland, Storsve, & Walhovd, 2017; Hirsiger et al., 2017).

Two components of attentional control are commonly described, bottom-up and top-down control (Bundesen, 1990; Cave & Wolfe, 1990; Duncan & Humphreys,

1989; Eriksen & Hoffman, 1972; Koch & Ullman, 1985; Posner, 1980; Treisman & Gelade, 1980; Yantis & Jonides, 1984). Bottom-up attention is commonly typified as exogenous, stimulus-driven attention and is said to be based on the properties of the stimulus such as saliency or onset (Borji et al., 2013; Itti & Koch, 2001). In contrast, top-down attention is typically referred to as endogenous, goal-directed attention and is concerned with how our prior knowledge, intentions and goals control visual selection (Carrasco, 2011).

The bottom-up versus top-down distinction is important for characterizing the age-related changes observed in visual performance (Hartley, Kieley, & Mckenzie, 1992; Madden, Whiting, Provenzale, & Huettel, 2004). Top-down attentional processes may minimize or inhibit stimulus-driven attentional capture (e.g., Bacon & Egeth, 1994) and the ability to do so is arguably one of the most frequently tested phenomena in attention and ageing research. The Inhibitory Control Deficit theory (Hasher & Zacks, 1988) posits that the ability to inhibit the processing of task irrelevant information declines with older age. This theory states that once irrelevant information is attended to, it receives sustained attention at the expense of the processing of task relevant information. Accordingly, it has been suggested that ageing is associated with a selective inability to effectively use top-down suppression of neural activity associated with distracting information (Gazzaley & D'esposito, 2007), in connection with a decreased involvement of dorsolateral prefrontal and parietal regions (Milham et al., 2002) and a reduced ability to switch between targets (Hampshire et al., 2008). Even in multifactorial theories of cognitive decline in ageing, declining performance arises from a combination of declines in attentional and neural resources, processing speed, and inhibition (Park & Festini, 2017).

However, the pattern of results in studies on attentional control and ageing is not always unequivocal. In the Simon task for instance, older adults show a deficit in attentional control compared to younger adults (Juncos-Rabadán, Pereiro, & Facal, 2008; Pick & Proctor, 1999; Vu & Proctor, 2008), even after correcting for slower response times in the older adults (Castel, Balota, Hutchison, Logan, & Yap, 2007; Van der Lubbe & Verleger, 2002). Some studies show a modulation of the

effect by complexity of the task (Kubo-Kawai & Kawai, 2010; Lee Salvatierra & Rosselli, 2011). Similarly, the reflexive or volitional orientation of attention towards peripheral cues show age-related effects only in specific conditions (Nobre, Nobre, & Kastner, 2014). Some studies even argued that the attentional control is preserved with advanced age (Lien, Gemperle, & Ruthruff, 2011).

The previous research on ageing and attentional control suggests that fine-grained and robust results obtained in well controlled experimental situations are also highly context dependent. Therefore, it is crucial to understand how the decline of attentional control impacts on day to day activities. Indeed, previous studies have linked declines in attentional control in older adults to problems in natural situations such as motor vehicle crash rates (Shinar et al., 1978), and the ability to adjust gait (Sparrow et al., 2002). In order to increase generalisability, some studies on attentional control have used more complex stimuli and focused on visual attention in natural scenes. This research has shown that information selection is influenced by bottom-up processes sensitive to features, as well as top-down influences (Henderson et al., 1999; Loftus & Mackworth, 1978; S. E. Palmer, 1975) such as scene context (Castelhano & Pereira, 2018), semantic informativeness (Henderson et al., 2007) or the observer's intention and understanding of a scene (Henderson, 2017). The age-related decline in attentional control might be linked to the change in the relative influence of top-down and bottom-up processes with age as bottom-up fixation selection loses strength or the role of top-down processes becomes more important (Açık et al., 2010).

Understanding the decline in the control of visual attention with ageing is particularly relevant for pedestrian safety. Indeed, older adults (above 75y/o) have the highest rate of pedestrian accidents in Australia (BITRE, 2015), and in the EU older adults make up nearly half of all pedestrian fatalities (ERSO, 2018). Studies on pedestrian behaviour in older adults have pointed towards deficits in cognitive processes as factors that might explain the high number of older adults involved in accidents (Nagamatsu et al., 2011). Specifically, attentional control abilities such as attention switching (Dommes et al., 2013), and executive function abilities such

as spatial planning (Geraghty et al., 2016) have been linked to fewer safe crossing decisions. These studies link executive functioning to performance in realistic tasks. However, they do not provide a fine-grained understanding of how declines in attentional control affect the visual exploration of the environment which, in turn, might impact performance. To the best of our knowledge, only one study, Zito et al. (2015), has linked visual sampling, executive functions, and road crossing decisions with age. In this study, both older adults and younger adults looked mostly at the appearing point of the vehicles. However, older adults spent more time than younger adults looking at the ground in front of them. Moreover, older adults made more unsafe crossing decisions and showed a decline in executive function as measured by the trail making task and the Clock Drawing Test.

The studies performed by Dommes et al. (2013); Geraghty et al. (2016) and Zito et al. (2015) investigated the impacts of ageing and executive function on visual exploration and road crossing performance together but not separately. Therefore, it is impossible to dissociate the impacts of executive function ability on visual exploration and road crossing behaviour, from the impact of ageing on visual exploration and road crossing behaviour. Alternatively, ageing with maintained executive function may not impact on visual exploration or road crossing behaviour at all. Older adults that do not show a decline in executive function may perform as safely as younger adults, as they may be aware of physical declines such as slower walking speeds (Bohannon, 1997; Thomas, Donovan, Dewhurst, & Bampouras, 2018). Moreover, maintained executive function abilities may allow older adults to compensate for their physical declines. To determine whether there is an impact of ageing without declining executive functions on visual exploration and road crossing behaviour I recruited participants from the Bournemouth University Ageing and Dementia Research Centre participant pool and from the Bournemouth branch of the University of the Third Age. I recruited from these groups as they are typically very physically, and socially active which helps to maintain executive function ability as individuals age (Carlson et al., 2008; Ybarra et al., 2008). Therefore, these participants are likely to have similar executive function abilities to younger adults. The similarity

in executive function abilities between older adults and younger adults allows assessing the impact of healthy ageing on attentional control, separately from executive functioning on decision making in a naturalistic task.

In the current study I assessed two main questions:

- Does ageing with maintained executive function abilities impact on crossing behaviour?
- Does ageing with maintained executive function abilities impact on visual exploration in a naturalistic dynamic scenario?

To answer these questions I presented older adults and younger adults with road traffic videos and recorded their road-crossing decisions and eye-movements. The videos contained distractors and a variety of traffic densities, as in Nicholls et al. (2019). I used automatic object detection techniques to measure, at each frame, the distance and the time to impact of the approaching vehicles. To confirm that our older adults showed similar executive function abilities to younger adults I tested their executive function abilities using the BADS zoo map test, and the Rogers and Monsell attention shift paradigm (RMA, Rogers & Monsell, 1995; B. A. Wilson, Alderman, Burgess, Emslie, & Evans, 1996). The BADS zoo map and the RMA tests were chosen as they had previously been linked to road crossing performance in older adults (Dommes et al., 2013; Geraghty et al., 2016).

## **3.2 Methods**

### **3.2.1 Participants**

64 participants were recruited, 31 older adults aged between 60 and 83 years old (y/o, mean=69.03, SE=1.38), and 33 younger adults aged between 18 and 35 y/o (mean=22.37, SE=0.91). All younger adults were recruited at Bournemouth University, UK. All participants had normal or corrected to normal vision. Participants were screened for mild cognitive impairment using the MoCA (Nasreddine et al., 2005). One older adult was excluded based on a cut-off score of 23 (Luis, Keegan,

& Mullan, 2009). Therefore 30 older adults and 33 younger adults were included in the final analyses. The study was approved by Bournemouth University’s ethics committee. Informed consent was obtained from participants prior to taking part. Participants took part in exchange for course credits or monetary compensation for their time. This study was performed in accordance with all appropriate institutional and international guidelines and regulations, in line with the principles of the Helsinki Declaration.

### **3.2.2 Apparatus**

During the experiment participants’ eye movements were recorded at a sampling rate of 1000Hz with the SR-Research EyeLink 1000 (with a chin and forehead rest), which has an average gaze position error of about  $0.25^\circ$  and a spatial resolution of  $0.01^\circ$ . Only the dominant eye was tracked. Stimuli were presented on an HP monitor with a screen resolution of 1920 by 1080 pixels, a width of 534mm and a height of 300mm, a horizontal viewing angle of  $46.9^\circ$  and a vertical viewing angle of  $27.4^\circ$  at a distance of 740mm. The experiment was coded in Matlab (MATLAB, 2016) using the Psychophysics toolbox, PTB-3 (Brainard, 1997) and EyeLink Toolbox extensions (Cornelissen et al., 2002). Calibrations for eye fixations were conducted at the beginning of the experiment using a nine-point fixation procedure as implemented in the EyeLink API (see EyeLink Manual) and using Matlab software. Calibrations were then validated with EyeLink software and repeated until there was less than  $1^\circ$  of error for every calibration point.

### **Executive Function Tests**

To assess the participants’ executive function abilities, participants completed the BADS zoo map test (B. A. Wilson et al., 1996), and the Rogers and Monsell attention shift paradigm (RMA; Rogers & Monsell, 1995). The BADS zoo map test assessed the participants’ spatial planning ability by assessing participants’ ability to plan a route around a zoo. In the first trial participants were given a map of a zoo and instructed to plan a route around a zoo, starting at the entrance and finishing with

a picnic. Along the route participants had to visit specified locations in any order while following set rules, such as only using specific paths twice and not visiting unspecified locations. Participants' planning time and time to complete the task was recorded. In the second trial participants had to plan a route around the same zoo, following the same rules, and visiting the same locations but in a specified order. Again, the participants' planning time and time to complete the task were recorded. Participants were scored based on visiting the correct locations and points were deducted when participants break the rules and exceed time limits for planning on the second trial. There was only one correct route in both trials, therefore, if participants did the task correctly their route for trial one would mostly match the route for trial two. The only exception being the order in which they went around a loop section of the map.

The RMA assessed participants' attentional control by getting participants to switch between two similar tasks. Participants were presented with number letter pairs (e.g., 9E) and depending on the position of the stimulus on the screen they either had to identify whether the number was odd or even or whether the letter was a vowel or consonant. For the RMA task I extracted the global and local switch costs as done by Rogers and Monsell (1995). The global switch costs refer to the difference in performance between a block where participants perform the same task and a block where participants are switching between tasks. Local switch costs refer to the differences in performance between switch and non-switch trials. These tests have previously been linked to road crossing ability (Dommes et al., 2013; Geraghty et al., 2016) and were designed to assess participants' spatial planning and attention shifting abilities.

### **3.2.3 Experimental Procedure**

I used the same video stimulus and design as in Nicholls et al. (2019). At the beginning of the experiment participants were informed that they would be presented with a series of videos of road crossing situations on screen and that they would have to indicate by pressing the spacebar on a keyboard when they could cross the

road and hold the button pressed for as long as they thought it was safe to cross. Participants were instructed to focus on approaching vehicles on the side of the road closest to them but vehicles did travel on both sides of the road (see Figure 3.1A for a capture of the scene). Vehicles travelled at an average velocity of 50 km/h. Each trial started with the presentation of a central fixation cross. Once the participants had fixated on the cross a blank screen was presented for 500 ms and then the video clip for the trial was presented (see Figure 3.1A). Each trial was followed by another blank screen for 500 ms and the next trial started with the central cross. One hundred trials were presented to the participants each with a different video clip, each lasting 10 seconds. All video clips were filmed at a real road crossing in Fribourg with a variety of traffic densities, with or without pedestrians and cyclists (distractors). The videos were completely natural, and no aspects of the videos were staged and they were not edited to control when the cars emerged. Thirty-five of the videos contained pedestrians. The camera was always fixed in the same location, at a height in between the average adult and the average child's height. All video clips were mirrored so as to simulate a road crossing in the UK. Critically, registration numbers were not identifiable and the visual scenes did not include any information allowing participants to identify where they were filmed. Prior to the experiment, 10 British drivers were asked where the video clips were located, all of whom responded with a location in the UK. Number of presses for each trial were collected and analysed for the purpose of the present experiment.

### **3.2.4 Statistical Analyses**

All statistical analyses and figures were performed and created using Matlab 2016a (MATLAB, 2016) and R (R Core Team, 2016).

#### **Crossing decisions**

For the sake of simplicity, I defined “time to impact” as the time that it would take for the closest approaching vehicle to reach the participants, from the moment when the participants stopped indicating that crossing was safe (i.e. when they released

the spacebar indicating that it was no longer safe to cross). This is illustrated in Figure 3.1D.

The number, and duration of crossing decisions, and time to impact were analysed with linear mixed models. Each of the models had fixed effects of age group (above or below 60y/o), traffic density, distractors, and zoo map score. Each of the models included two interactions one between age group and traffic density, and one between age group and distractors. The model for time to impact and number of crossing decisions also included random intercepts for each participant and video and random slopes for zoo map score. The model of button press duration only included random intercepts for each participant and each video. To begin with, each of the models contained random slopes for each fixed factor and interaction but the model did not converge so the random effects structure was pruned using the procedure proposed by Bates, Mächler, Bolker, and Walker (2015). Initially the model contained additional fixed effects of MoCA score, response time on the RMA, local switch cost on accuracy score of the RMA, the local switch cost on response time on the RMA, global switch cost on accuracy of the RMA, and global switch cost on response time on the RMA. This model did not converge so a lasso regression was used to determine which fixed effects could be removed (Tibshirani, 1996). Lasso regression is used for variable selection and functions similarly to ridge regression by shrinking large regression coefficients to reduce overfitting. This is achieved by forcing the sum of the absolute value of regression coefficients to be less than a fixed value. The difference between ridge regression and lasso regression is that this shrinking process forces some coefficients to be set to zero in the lasso regression but not in the ridge regression. Forcing these coefficients to be set to zero is the equivalent of removing these coefficients from the regression (Tibshirani, 1996).

Linear mixed models were chosen as they have a number of advantages over non-mixed methods as well as mixed-ANOVAS. For example, linear mixed models allow researchers to simultaneously consider all factors which potentially contribute to the understanding of data, including fixed and random effects (Baayen, Davidson, & Bates, 2008). Linear mixed models have more power than mixed ANOVAs be-

cause linear mixed models are able to simultaneously accommodate by item and by participant subject variation (Barr, Levy, Scheepers, & Tily, 2013). Linear mixed models are also well suited to naturalistic experiments as they are able to take into account large unbalanced data sets and missing data (Baayen et al., 2008).

For each video clip the presence of a human distractor was encoded in a dichotomous way (1 for one or more human distractors present in the trial, 0 for no human distractors in the trial). The number of vehicles and vehicle locations at each video frame were determined using a custom automatic car detection algorithm. The vehicle locations were used to calculate the time to impact. Our method combines a Matlab car detection algorithm using Gaussian mixture models (Kingdom, 2017) and a Kalman filter (Kingdom, 2019). The car detection algorithm detects and counts cars using a foreground detector via Gaussian mixture models and then performs a Blob Analysis on the detected foreground objects. I applied the Kalman filter to reduce the number of times the objects were lost (Figure 3.1A). To further improve the performance of the foreground detector I created difference videos from the stimuli videos. In the difference videos, each frame was created by subtracting the previous frame in the original video from the current one (Figure 3.1B). Moreover, the motion in each difference video was enhanced using the Eulerian magnification toolbox (Wu et al., 2012). I amplified the motion so that the vehicles blurred into one very bright object – including larger vehicles (such as trucks) which would often be detected as two objects by the car detection algorithm (Figure 3.1C; I used a bandpass between 0.4 and 3Hz,  $\alpha=40$ ,  $\lambda=80$ ). A marker was then placed in the video at known distances along the road and the time at which the car passed over these markers was calculated (Figure 3.1A). Location and time were used to calculate how long it would take the vehicles to reach the participants from the time the key was released indicating safe crossing; i.e. the time to impact when the crossing was considered unsafe. A large value would indicate an early and safe decision.

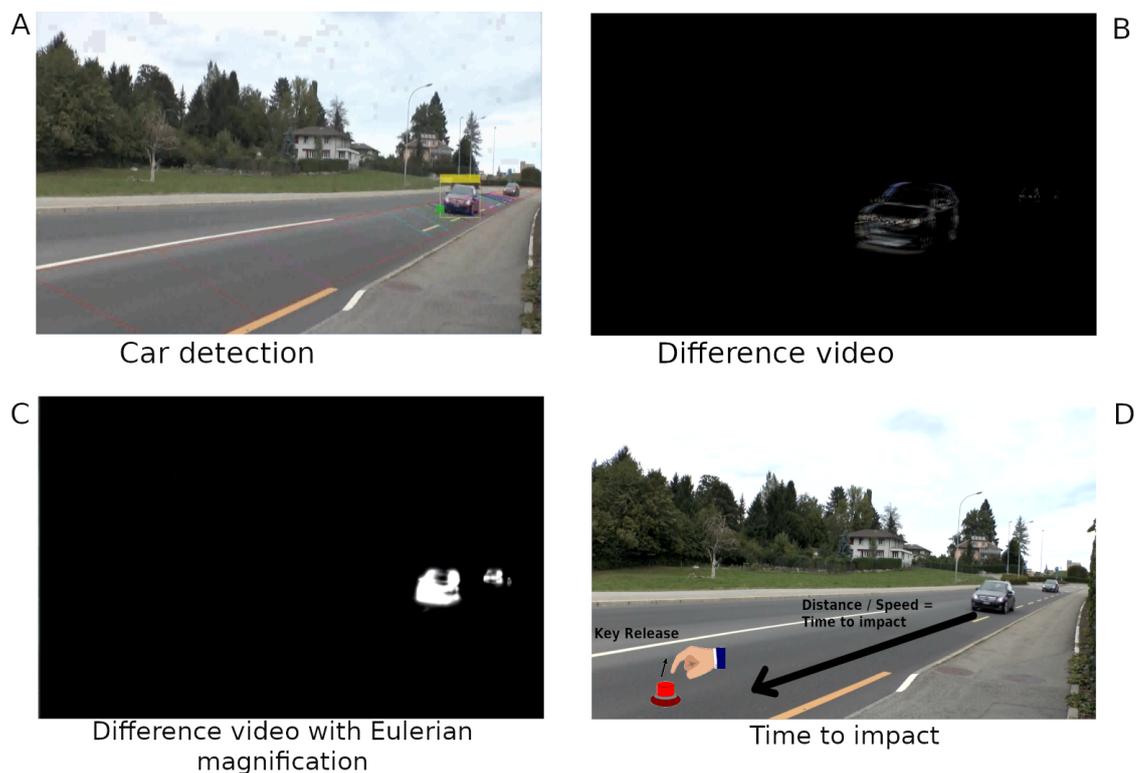
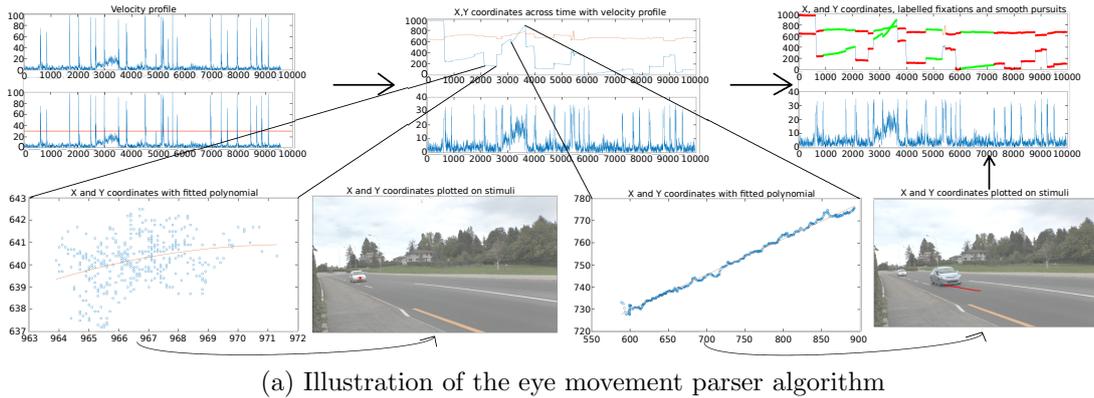


Figure 3.1: Illustration of the car detection algorithm. (A) Screenshot of the car detection algorithm on original stimuli. Coloured markers on the road indicate where car distance is calculated. (B) Difference video. (C) Difference video features magnified by the Eulerian magnification (see Methods for magnification procedure). (D) Illustration of the time to impact measure (see Methods for calculation).

### Executive function tests

Differences between older adults and younger adults on all measures were determined using a bootstrap t-test with a one step M-estimator. Multiple comparisons were corrected using the Hochberg method. I used bootstrap t-tests as they handle skewed distributions and outliers better than the Student's t-test. They are able to do this by creating t-distributions that are closer in shape to the sample distribution and can be used with any estimate of central tendency, creating better confidence interval estimates. (Rousselet, Pernet, & Wilcox, 2019). Bayes factors were also calculated using the BayesFactor package in R (Morey & Rouder, 2018), after outliers were removed using the median absolute deviation rule.

## Parsing of eye movements



(a) Illustration of the eye movement parser algorithm

Figure 3.2: Illustration of eye movement parser algorithm. Top left – velocity threshold to extract saccades (bottom panel). Velocity of eye movement samples (top panel). Top centre – plotting X and Y coordinates of eye movement samples across whole trial (top panel). Bottom left and right – extraction of segments of eye movement samples maintaining a velocity of 30 deg/s for at least 100 ms with a polynomial fitted to the segments. Beside these are X and Y coordinates of the segments plotted on matching frames of the experiment stimuli. Top right – completed labelling of eye movements as fixations (red lines), smooth pursuits (green lines), and saccades (blue lines) for a whole trial.

Eye movements were parsed into fixations, saccades and smooth pursuits using a custom algorithm (see Nicholls et al., 2019). Previous studies examining properties of smooth pursuit eye movements have typically calculated smooth pursuit gain, which is the ratio between eye velocity and target velocity (e.g. Maruta, Suh, Niogi, Mukherjee, & Ghajar, 2010; Stubbs, Corrow, Kiang, Panenka, & Barton, 2018). This requires knowledge of the target velocity and in realistic videos, the target changes and it requires sophisticated image analysis to determine the velocity of cars from videos. Other techniques for parsing smooth pursuit eye movements from fixations and saccades which do not require knowledge of the target have been developed. These are based on dual velocity thresholds, velocity and dispersion, and principal component analysis, with and without binocular eye tracking (Komogortsev & Karpov, 2013; Larsson, Nyström, Andersson, & Stridh, 2015; Larsson, Nyström, Ardö, Åström, & Stridh, 2016). The algorithm combining velocity, and dispersion information works very effectively for moving dot and image stimuli but they did not work very effectively for realistic videos (Larsson et al., 2016). Another approach using machine learning was also shown to be effective on moving dot stimuli (Vidal,

Bulling, & Gellersen, 2012), however, it has not been tested on realistic video stimuli and it requires the development of a training set. To my knowledge there is no algorithm that separates out smooth pursuits from fixations effectively for realistic video stimuli, therefore, I created my own. The advantages of this algorithm are that it effectively labels saccades, fixations, and smooth pursuits from data recorded when participants gazed at a realistic stimuli, without knowing the velocity of the cars, and only needing monocular tracking data. Below I describe how the custom algorithm works.

Saccades were extracted using a manually set velocity threshold starting with a threshold at  $30^\circ/\text{s}$  to match the EyeLink Manual, increasing to a maximum of  $80^\circ/\text{s}$ , if the first threshold was too low for the a given participant. I changed the velocities manually at an individual level to adapt to the differing levels of noise present in different participants. Noise might be caused by factors related to the stability of the participant's eye which vary with age and any medication used. Noise can also be caused by factors related to the stability of the recorded eye movement signal such as dryness of the eye, makeup, occlusion due to the eyelid, reflections from glasses, etc. The Eyelink setting is acceptable on average but can sometimes lead to misrepresentations at an individual level which can bias the sample distribution. If the majority of samples in the trial were above the maximum velocity threshold then the trial was removed and if more than 50% of the trials were removed then the participant was excluded. In total, 77 trials were removed, and two participants were excluded for noisy recording.

Potential smooth pursuit segments were first isolated as segments for which velocity was maintained below or equal to  $30^\circ/\text{s}$  for a minimum of 100ms. From this initial extraction, smooth pursuit segments were identified using a dispersion threshold, based on the following algorithm. A polynomial was fitted to the X and Y coordinates of the gaze samples in each smooth eye movement segment, after having removed outliers using the Corr v2 toolbox (Pernet et al., 2013). The root-mean square error of the polynomial fit was then calculated and divided by the exponential of the arc length (calculated using the arclength toolbox, D'Errico, 2010) of

the polynomial. A threshold was set at  $1 \times 10^{-9}$  and samples below that threshold were considered as smooth pursuit, while samples above were considered as part of a fixation. This algorithm is summarized in Figure 3.2 and the following equation:

$$P_{RMSE} / \exp(A)$$

$P_{RMSE}$  is the root mean square error of the polynomial line,  $A$  is the arc length of the polynomial line.

### Statistical analysis of eye movements

Gaze samples were analysed using gaze similarity matrices. Gaze similarity matrices were computed by creating smoothed (Gaussian kernel =  $4^\circ$  of visual angle) Z-scored maps of the gaze positions. The Fisher transformed correlations between the gaze map on a single trial and the gaze maps for all other trials were calculated (Figures 3.4A,B). The mean similarity between the gaze map on a single trial and all the other maps was then computed for each age group with the bootstrap confidence intervals (Figure 3.4C). Statistical maps were calculated using the iMap toolbox, version 4 (Lao et al., 2017). iMap computes pixel-wise linear mixed models (LMMs) across participants and trials on each z-score gaze map. The z-score gaze map is created by pooling together fixation, and smooth pursuit gaze positions. The gaze maps pool the gaze positions across the entire video duration. The gaze maps are then z-scored. After the pixel-wise LMM is computed iMap uses a universal bootstrap clustering test to resolve biases in parameter estimation and problems arising from multiple comparisons (Pernet et al., 2011, 2015). The bootstrap clustering works in the following way. For each pixel in the image an LMM is computed with pixel intensity (combined gaze frequency and duration) as the response variable for each pixel in the gaze map to produce a statistical gaze map. IMap also computes the F and p values for each of the LMMs. The outputted statistical map is thresholded at  $p < 0.05$ . From the thresholded map iMap records the maximum cluster characteristic across all significant clusters in the statistic map. IMap then randomly shuffles the response variable and randomly draws with replacement new values for the response

variable, the predictor variable, and the error. Another LMM is calculated and again the resulting statistic maps are thresholded and the maximum cluster characteristics are recorded. This process is repeated a large number of times to get a distribution of the cluster characteristic under the null hypothesis. The original statistic map calculated by iMap is then thresholded at  $p < 0.05$  and iMap compares the selected cluster characteristic with the value of the null distribution corresponding to the 95th percentile. Any cluster with the chosen cluster characteristic larger than this threshold is considered significant.

The linear mixed model used for iMap had the same fixed effects structure as the model used with the time to impact data. This model only included random intercepts for each participant and each video but no random slopes. This model started with random slopes for each fixed factor and interaction but did not converge. The same pruning procedure I used for the time to impact data was used for the iMap linear mixed model. The aim in using iMap was to determine where participants looked during the videos, how this changes depending on changes in the scene such as the presence of pedestrians or changes in traffic density, and how this changes across the lifespan.

### 3.3 Results

#### Executive functions

Older adults performed to the same level as younger adults on the MoCA ( $t=0.11$ ,  $df=34.10$ ,  $p=0.985$ ,  $d=0.02$ , Bayes factor(BF)=0.26, Figure B.1A in Appendix B), BADS zoo map ( $t=0.07$ ,  $df=34.70$ ,  $p=0.928$ ,  $d=0.05$ , BF=0.27, Figure B.1B), RMA local switch cost ( $t=0.003$ ,  $df=31.53$ ,  $p=0.944$ ,  $d=0.1$ , BF=0.62, Figure B.1C), and RMA global switch cost ( $t=0.18$ ,  $df=28.84$ ,  $p=0.062$ ,  $d=0.54$ , BF=2.91, Figure B.1D). In contrast, the overall latencies on the RMA were longer for older adults than younger adults ( $t=3.84$ ,  $df=22.14$ ,  $p < 0.05$ ,  $d=0.88$ , BF=4852.99 Figure B.1E).

### 3.3.1 Crossing decisions

To assess how risky or conservative the crossing strategies were, I measured the time to impact. In other words, I measured how long it would take for the moving vehicle to reach the participant (how far away the vehicle was) when the participant judged that crossing was no longer safe (released the crossing key). I then assessed how the time to impact was influenced by traffic density, distractors, age group, and executive functioning. Linear mixed model results showed a significant interaction between age group and traffic density on the time to impact of the car ( $\beta=61.29$ ,  $SE=25.09$ ,  $t=2.44$ ,  $p=0.015$ , Figure 3.3D). The difference in time to impact between older adults and younger adults was larger for high traffic density. See Tables B.1-B.3 for full linear mixed model results. Across all traffic densities, older adults had larger time to impact than younger adults (bootstrapped t-test:  $t=10.18$ ,  $df=852.91$ ,  $p<0.05$ ,  $d=0.35$  Figure 3.3C), suggesting more conservative crossing strategies for older adults. This difference increased with increasing traffic density – one car on the road ( $t=-0.92$ ,  $df=33.72$ ,  $p=0.355$ ,  $d=0.17$ , Figure 3.3D), four cars on the road ( $t=-4.24$ ,  $df=203.69$ ,  $p<0.05$ ,  $d=0.29$ , Figure 3.3D), and seven cars on the road ( $t=-2.87$ ,  $df=26.92$ ,  $p<0.05$ ,  $d=0.57$ , Figure 3.3D). In line with the results on time to impact, older adults decided to cross the road less often than younger adults ( $t=8.4971$ ,  $df=2424.67$ ,  $p<0.05$ ,  $d=0.2$ , Figure 3.3A). The duration of the mean key presses per participant was not significantly different between age groups ( $t=0.97$ ,  $df=2382.30$ ,  $p=0.31$ ,  $d=0.02$ , Figure 3.3B). This implies that on average younger adults decided to cross the road for a longer total time (number of crossing decisions x average key press duration), thus adopting a riskier crossing strategy. There was no effect of distractors or BADS scores on the time to impact and number of crossing decisions (See Appendix B).

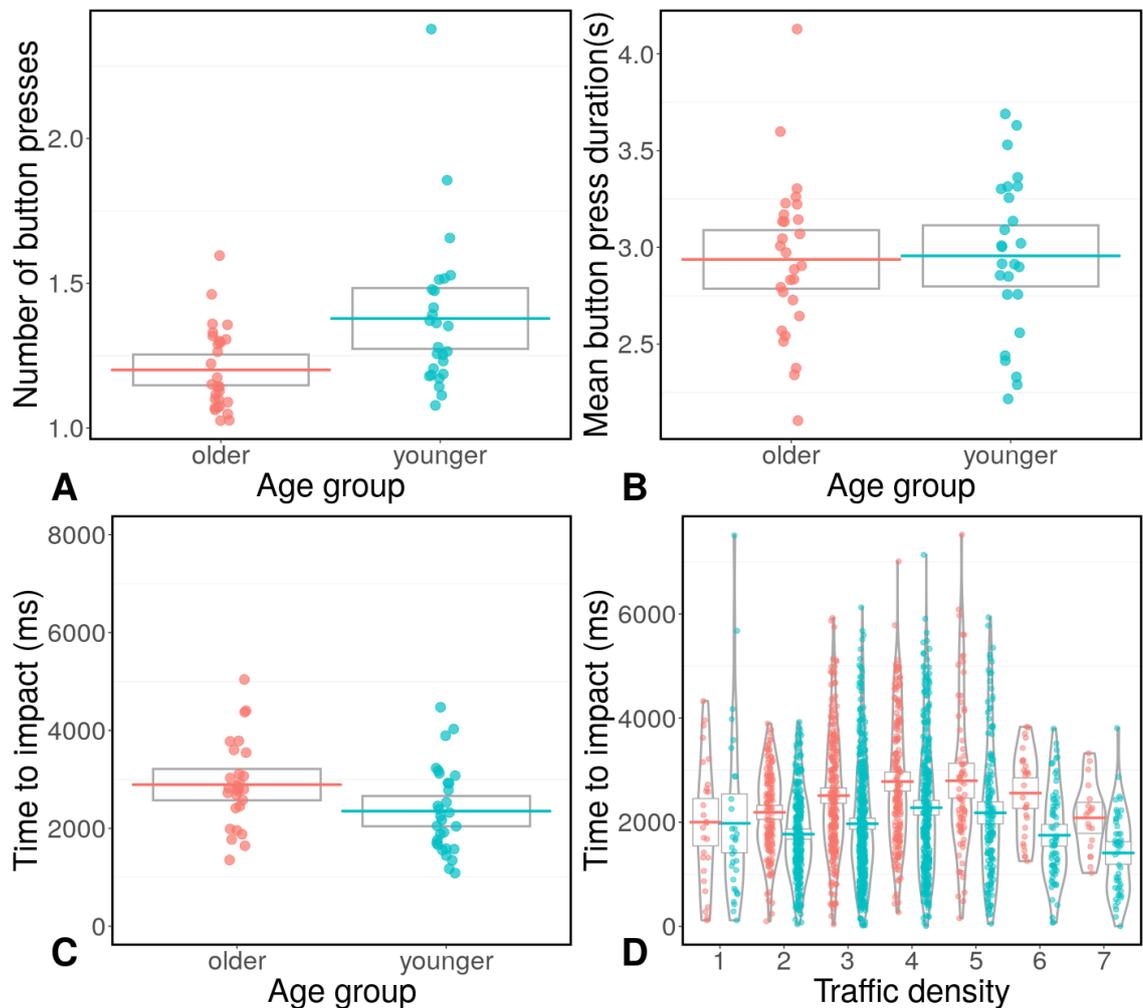


Figure 3.3: Crossing decisions for older adults and younger adults. (A) Mean number of crossing decisions. (B) Mean duration of button presses. (C) Mean time to impact, (D) time to impact at different traffic densities. In all panels, older adults are shown with red points and younger adults with blue points.

### 3.3.2 Eye movement results

#### Gaze similarity

I investigated the variability in gaze patterns across trials and age groups through gaze similarity matrices. Gaze similarity matrices are based on pairwise correlations between the trials' smoothed gaze maps. Thus, gaze similarity matrices reveal the consistency in gaze locations through the experiment (across trials). Figure 3.4C shows, for each of the 100 trials, the sorted average correlations between their gaze maps and the gaze maps generated by the other 99 trials. The shaded areas represent bootstrap confidence intervals across participants. Older adults and younger adults show similar levels of gaze variability across the experiment (Figures 3.4A,B) which

is highlighted by the overlapping confidence intervals (Figure 3.4C).

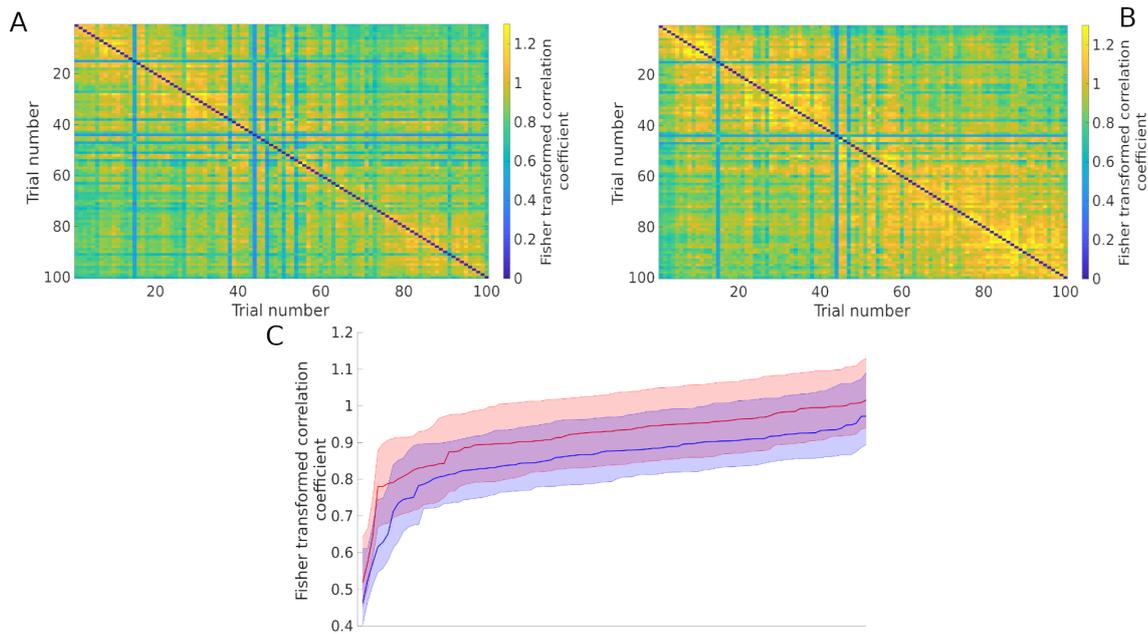


Figure 3.4: Gaze similarity matrices for younger adults (A) and older adults (B). Panel (C) shows the bootstrap means and confidence intervals for each group. Older adults are shown in red and younger adults are shown in blue

### Statistical gaze maps

The iMap analysis with fixed effects of age, distractors, task difficulty, and BADS scores, showed that both older adults and younger adults looked mainly at the appearing point of the cars (Figure 3.5A,B). The appearing point might be the optimal viewing location for the task. However, younger adults explore the stimulus space slightly more than older adults (larger significant gaze area) pooled across time. As interactive effects are difficult to interpret in statistical maps, I tested the simple effects of distractors and traffic density for each age group. When pedestrian distractors were present in the scene, older adults' gaze was drawn to the sidewalk where pedestrians appear from (Figure 3.5C). Younger adults' gaze was not significantly impacted by the presence of distractors (Figure 3.5D). Older and younger adults' gaze was not significantly impacted by traffic density or their BADS zoo map scores.

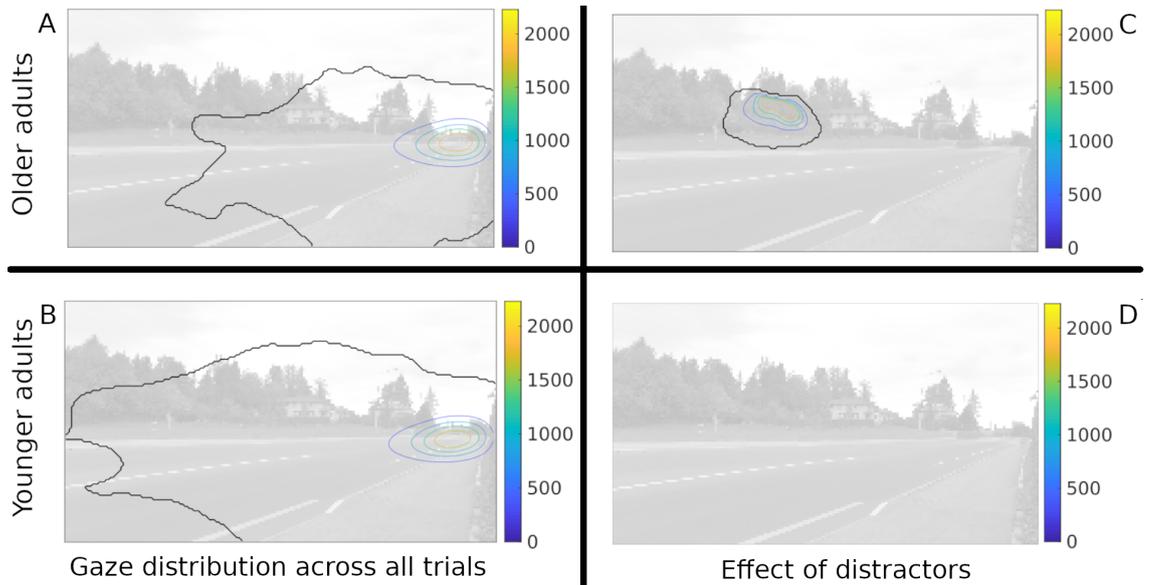


Figure 3.5: Statistical gaze maps. Gaze density contours are only plotted within significant areas. Black contour lines encircle significant areas. For all panels the larger the beta values and the brighter the contour lines the more participants gaze in those locations. The scales are determined by taking the maximum and minimum beta coefficient across all the statistical gaze maps for a particular LMM result. Beta maps for older adults (A) and younger adults (B). Beta maps for each age group were produced by running a one-sample t-test of the group gaze map against the mean gaze map for all trials and participants. The simple effect of distractors on older adults' (C) and younger adults' (D) gaze locations.

### 3.4 Discussion

I recorded eye movements of older adults and younger adults while they watched videos of road traffic and indicated when they could cross the road. I also measured some executive subcomponents to dissociate the impact of executive functioning from the impact of healthy ageing on visual exploration and crossing behaviour. In this study, the healthy older adults and the younger adults showed similar performance on our executive function measures (spatial planning and attention switching). Although the switching cost was similar for both age groups, older adults were generally slower than younger adults during the switching task. Eye movement data revealed that both older adults and younger adults look mainly at the appearing point of the cars. However, pedestrian distractors attracted older adults' overt attention, which was not the case for younger adults. Older adults typically made fewer and safer (larger time to impact) crossing decisions compared to the younger

adults.

As mentioned in the introduction I recruited older adults from the Ageing and Dementia Research Centre participant pool and the local University of the 3rd age branch. These older adults tend to be very physically, and socially active, which can play a role in maintaining their executive function ability (Carlson et al., 2008; Ybarra et al., 2008). Indeed, I found that these older adults had similar executive function abilities to younger adults. As this older adult population showed no decline in executive function abilities this afforded us a rare opportunity to determine if ageing with maintained executive function impacted on visual exploration and road crossing behaviour.

### **3.4.1 Does ageing with maintained executive function abilities impact on crossing behaviour?**

Older adults typically made fewer crossing decisions and had a larger time to impact than younger adults. This suggests that older adults show different crossing behaviour to younger adults. Although the crossing behaviour was different between the two age groups, for older adults this was a positive difference. Making fewer crossing decisions reduces the likelihood of an accident through exposure (Keall, 1995). A larger time to impact would allow participants longer to cross at a real road crossing. Longer times to cross would allow older adults to compensate for potentially slower walking speeds (Bohannon, 1997; Thomas et al., 2018) or reaction times as suggested by Lobjois and Cavallo (2007). Similarly, it is possible that the older adults in our study took into account their cognitive slowing when making crossing decisions. It has also been suggested that older adults can recruit additional neural resources in the frontal lobes in order to perform at the same level as younger adults, at least in simplistic scenarios like the one-way road in our experiment. However, on tasks that are more complex the resource ceiling is reached and older adults are no longer able to perform at the same level as younger adults (Reuter-Lorenz & Cappell, 2008). Therefore, it will be critical that future studies determine if compensatory strategies are still effective in more complex environments that are more

taxing for older adults executive functioning.

Overall I find that so long as older adults are able to remain healthy and maintain their executive function abilities, they are able to make safe crossing decisions later in life.

### **3.4.2 Does ageing with maintained executive function abilities impact on visual exploration in a naturalistic dynamic scenario?**

For both age groups, the appearing point of the vehicles was the preferred viewing location as overt visual attention was principally oriented towards it. This suggests that the appearing point is an optimal location to sample diagnostic information for the crossing task. Despite their good performance in the executive function tasks, the older adults overt attention was attracted by distractors, away from the otherwise preferred viewing location. younger adults did not show this attentional bias. This suggests that older adults were less able to inhibit attentional capture towards task-irrelevant distractors than younger adults, which is consistent with previous research (Crawford et al., 2013; Milham et al., 2002; Olincy et al., 1997). The finding that for the most part older adults focus on the appearing point is consistent with a recent finding showing that older adults can modulate their attention in the same way as younger adults (Hilton, Miellet, Slattery, & Wiener, 2019).

Even though older adults' overt attention was captured by pedestrian distractors they were still able to make safe crossing decisions. Therefore, I cannot rule out an alternate explanation for the eye tracking results. As older adults made fewer crossing decisions and released the button earlier than younger adults they have more time to look at pedestrians in the scene. Therefore, older adults may voluntarily focus their overt attention on pedestrian distractors. To avoid missing new cars entering the road older adults might simultaneously employ their covert attention to attend to the appearing point. To determine whether older adults attention is captured by pedestrian distractors due to a decline in inhibitory control or whether older adults voluntarily gaze at pedestrian distractors and covertly attend to cars,

the roles of covert and overt attention would need to be investigated. I intend to investigate the use of overt and covert attention in older adults and younger adults in road crossing situations. To this aim, I will use an approach that I recently developed and which is based on eye-tracking and Steady State Visual Evoked Potentials (de Lissa, Caldara, Nicholls, & Miellet, 2020). In this study, I showed that covert shifts of attention may reduce visual processing of objects even when they are directly tracked with the eyes.

Overall our results point towards providing support for the predictions made in the Inhibitory Control Deficit Theory, that participants' top-down inhibition over stimulus-driven attentional capture decreases with age. However, I cannot rule out the possibility that older adults voluntarily gaze at pedestrians.

### **3.4.3 Conclusion**

In summary, while in this study older adults showed a general cognitive slowing and had their visual attention captured by distractors, they were able to make safe crossing decisions. This was achieved by adopting a conservative strategy of crossing less often and choosing larger crossing gaps (larger time to impact). This finding is important as it helps eliminate healthily ageing older adults as a group that requires intervention to improve the safety of their crossing behaviour on one-way roads. Therefore, training methods or infrastructure changes should be focused on assisting older adults that show declines in executive function to make safe crossing decisions on one-way roads.

In a more complex situation, such as a two-way street crossing, healthily ageing older adults may have more difficulties. It has been suggested that older adults can recruit additional neural resources in the frontal lobes in order to perform at the same level as younger adults. However, on tasks that are more complex the resource ceiling is reached and older adults are no longer able to perform at the same level as younger adults (Reuter-Lorenz & Cappell, 2008). Considering that the current study used an environment with a single lane of traffic, it will be critical that future studies determine if compensatory strategies are still effective in more complex

environments that are more taxing on older adults executive functioning. Using virtual reality, I will systematically manipulate the number of driving directions and lanes in future studies in order to formally address this question and to explore how the situation complexity interacts with executive function to impact visual exploration, attentional control and decision making for pedestrians.

# Chapter 4

## Ageing and executive function decline lead to performance decline in challenging naturalistic road crossing situations

### 4.1 Introduction

In this introduction I will give an overview of how visual attentional control declines with age, and how this can impact everyday activities of older adults (OAs). I then focus on how a decline in attentional control abilities specifically affects older adults' road crossing behaviour. I then discuss my findings from Chapter 3 and how these can be built upon using a more complex road crossing task. I finish with the questions that I aim to address with my experiments in this chapter.

As we age many perceptual and cognitive abilities decline. The declining abilities include visual attentional control, such as the ability to suppress task-irrelevant distractors (Milham et al., 2002) or the ability to switch between targets (Hampshire et al., 2008). They also include executive functioning abilities such as inhibition (Beurskens & Bock, 2012; Butler et al., 1999; Butler & Zacks, 2006; Hampshire et al., 2008; Harsay et al., 2010; Milham et al., 2002; Nieuwenhuis et al., 2000; Olincy et al., 1997; Tipper, 1991), planning (Allain et al., 2005), working memory (Anders,

Fozard, & Lillyquist, 1972; Van der Linden, Brédart, & Beerten, 1994), and cognitive flexibility (S. Daigneault, Braun, & Whitaker, 1992; Eppinger, Kray, Mecklinger, & John, 2007). Age related decline in visual attention and executive functioning ability have been associated with a reduction in frontal lobe activation (Gazzaley & D'Esposito, 2007; Hampshire et al., 2008; Milham et al., 2002; Salat et al., 2004), including the dorsolateral prefrontal cortex (DLPFC, Rypma & D'Esposito, 2000), the ventrolateral PFC (VPFC) and the posterior parietal cortex (PPC, Hampshire et al., 2008).

Age related deficits in visual attentional control and executive functioning have been associated with difficulties in the real world. For example, OAs are more likely to fall over than younger adults (YAs). Visual attentional control has been linked to OAs' risk of falling as OAs tend to fixate stepping targets for longer than YAs (Chapman & Hollands, 2006b; Zietz & Hollands, 2009), suggesting that OAs need longer to process the necessary visual information to plan their steps. OAs that had a high risk of falling, however, tended to look away from the stepping target prematurely (Chapman & Hollands, 2006b, 2007). This tendency to look away prematurely has been associated with a reduction in the accuracy and precision of OAs steps (Chapman & Hollands, 2006b, 2007). One suggested interpretation is that OAs at a higher risk of falling are not taking the time to process the necessary visual information to make an accurate step (Chapman & Hollands, 2006b, 2007). The decline in executive function in OAs has also been associated with a decline in general daily living skills (Hart & Bean, 2010). For instance, a decline in certain aspects of executive functioning such as spatial planning has been associated with participants making less safe road crossing decisions (Geraghty et al., 2016).

Focusing on the impact of ageing and declining executive functions on road crossing ability, OAs have been shown to be particularly vulnerable in road crossing situations with almost 50% of road traffic accidents in the EU in 2014 (ERSO, 2018) involving adults aged 65 or above (for more information see Chapter 1). Previous research investigating why OAs are particularly vulnerable have pointed towards visual attentional control and executive functioning, in particular attention switching

and spatial planning, as being important factors in OAs ability to make safe crossing decisions (Dommes et al., 2013; Geraghty et al., 2016; Zito et al., 2015). These studies link executive functioning to performance in realistic tasks. However, they do not provide a fine-grained understanding of how a decline in attentional control affects the visual exploration of the road crossing environment which, in turn, might impact performance.

In the previous chapter I investigated how ageing with maintained executive functioning affected the exploration of the road crossing environment and how this impacted on road crossing performance. I found that OAs were able to make safe crossing decisions, and even took into account their slower response times. In contrast to previous research, my findings suggested that older participants adopt a more conservative crossing strategy characterised by less frequent crossing decisions and larger crossing gaps. The road crossing scene in the previous chapter was relatively simple with one direction of traffic. Therefore, it would be interesting to investigate the impact of healthy ageing and executive functioning level on performance when we parametrically manipulate the situational complexity. Indeed, previous literature has suggested that OAs are able to make safe crossing decisions in simple situations, such as when cars only come from one direction, but have difficulties in more complex situations such as when cars travelled from both directions (Oxley, Fildes, Ihsen, Charlton, & Day, 1997), cars travelled in the far lane (Geraghty et al., 2016; Oxley et al., 1997, 2005), or when cars travelled quickly (Dommes et al., 2013; Lobjois & Cavallo, 2007; Oxley et al., 2005). These studies have separately addressed the effect of specific traffic situations, such as cars travelling from both directions, and the effect of executive functioning, or the combined effect of car speed and a decline in executive functioning on the ability to make safe crossing decisions. None of them have examined the combined effect of declining executive functioning, cars coming from both directions and car speed or traffic density. In the current experiment I assessed these combined effects to see whether there are specific situations that OAs have difficulties with and whether declining executive functions amplify these difficulties.

To this aim I performed two virtual reality (VR) experiments, assessed participants' spatial planning abilities using the BADS zoo map test (B. A. Wilson et al., 1996) and their attention switching abilities using the Rogers and Monsell attention switching (RMA) task (Rogers & Monsell, 1995). I also measured the participants' average walking speed. To increase participants' ability to immerse themselves in the scenario and allow them to integrate information across different hemifields, I presented the stimuli with a large horizontal field of view of 180°. As in previous experiments, I recorded eye movements, and crossing decisions. In this experiment I also recorded head movements to allow us to calculate eye movement positions when participants looked at the screens to their left and right hand sides. I used a VR setup as it enabled participants to be repeatedly exposed to a variety of realistic hazardous traffic situations without the threat of enduring injury (Meir, Parmet, & Oron-Gilad, 2013; Schwebel, Gaines, & Severson, 2008; Schwebel et al., 2012).

As mentioned in Chapter 3, OAs responded to only one lane of traffic and one travel direction. In the VR environment, I included two traffic directions in order to make the task more realistic and more taxing for executive functioning. Thus, if any difference would be observed between both studies, I would be unable to disentangle the influence of the number of lanes from the influence of the number of traffic directions as these variables would be confounded. To address this confound I conducted two experiments. In the first experiment I included only one traffic direction and I manipulated the car speed and the number of lanes, one or two. When only one lane was used, it could either be the near or the far lane. This design allowed us to investigate the effect of task complexity on visual exploration and crossing decisions via the number of traffic lanes, the effect of car speed and their interaction. The near vs far lane contrast also offered a way to explore a potential influence of the distance of the moving vehicle as well as its interaction with speed as suggested by Geraghty et al. (2016); Oxley et al. (1997) and Oxley et al. (2005). The VR environment that I used had an obscured view of the cars on the left-hand side compared to the field of view on the right hand side. This gave us the opportunity to see if OAs have difficulties with a restricted view of the cars in

the same way children do (Ampofo-Boateng & Thomson, 1990; Meir et al., 2013). In the second experiment, cars always appeared on both lanes and I manipulated the car speed, cars travelling from one direction or both directions, traffic density, obscured or non-obscured viewpoint, and task-irrelevant distractors.

My overarching question for both experiments is: Do OAs and participants with poorer executive functioning abilities make riskier crossing decisions when task complexity is increased than YAs and participants with better executive functioning abilities?

I define riskier crossing decisions as any decisions that would increase the likelihood of an accident. For example, through making more crossing decisions or leaving less time to impact in a more complex situation than in a simpler situation. For Experiment 1 I increase task complexity in the following ways:

- Increasing car speed.
- Obscuring the viewpoint of the oncoming cars.
- Changing the lane (near/far) cars travel in.
- Change the number of lanes (one/two) cars travel in.

## 4.2 Methods – Experiment 1

### 4.2.1 Participants

Fifty-three participants were recruited, 19 aged between 65 and 85 years old (y/o, mean=70.80, SE=1.31), and 34 aged between 18 and 24 y/o (mean=19.94, SE=0.26). The recruitment of OAs was cut short due to the COVID-19 pandemic. All YAs were recruited at Bournemouth University, UK. Older adults were recruited either from the Bournemouth Ageing and Dementia Research Centre (ADRC) participant pool or from the Wimborne branch of the University of the Third Age. All participants had normal or corrected to normal vision. Participants were screened for mild cognitive impairment using the Montreal Cognitive Assessment (MoCA, Nasreddine et al., 2005). No participants scored below the cut off score of 23 (Luis et al., 2009).

Therefore all recruited participants were included in the final analyses. The study was approved by Bournemouth University's ethics committee. Informed consent was obtained from participants prior to taking part. Participants took part in exchange for course credits or monetary compensation for their time. This study was performed in accordance with all appropriate institutional and international guidelines and regulations, in line with the principles of the Helsinki Declaration.

#### **4.2.2 Executive function tests**

To assess the participants' EF abilities, participants completed the BADS zoo map test (B. A. Wilson et al., 1996), and the Rogers and Monsell attention shift paradigm (RMA; Rogers & Monsell, 1995). The BADS zoo map test assessed the participants' spatial planning ability by assessing participants' ability to plan a route around a zoo. In the first trial participants were given a map of a zoo and instructed to plan a route around a zoo, starting at the entrance and finishing with a picnic. Along the route participants had to visit specified locations in any order while they followed set rules, such as only using specified paths twice and not visiting unspecified locations. Participants' planning time and time to complete the task was recorded. In the second trial participants had to plan a route around the same zoo, followed the same rules, and visited the same locations but in a specified order. Again, the participants' planning time and time to complete the task was recorded. Participants' performance was assessed based on visiting the correct locations and points were deducted when participants broke the rules and exceed time limits for planning on the second trial. The scores ranged from zero to four, the higher the score the better participants performed on the test.

The RMA assesses participants' attentional control by getting participants to switch between two similar tasks. Participants were presented with number letter pairs (e.g., 9E) and depending on the position of the stimulus on the screen they either had to identify whether the number was odd or even or whether the letter was a vowel or consonant. For the RMA task I extracted the global and local switch costs as done by Rogers and Monsell (1995). The global switch costs refer to the difference

in performance between a block where participants perform the same task and a block where participants are switching between tasks. Local switch costs refer to the differences in performance between switch and non-switch trials. I also extracted the participants' accuracy and response times on each trial of the RMA. Correct responses were scored as one, incorrect responses as zero. Individual performance was then assessed by averaging accuracy over the entire RMA experiment.

These tests have previously been linked to road crossing ability (Dommes et al., 2013; Geraghty et al., 2016) and were designed to assess participants' spatial planning and attention shifting abilities.

### **4.2.3 Walking speed**

I measured participant's walking speed by asking participants to walk along a nine meter corridor while measuring their walking time. Participants were asked to walk at their normal day to day walking pace. This was done three times and an average walking time was then calculated. The walking speed was then calculated by dividing the nine meter distance by this average walking time.

### **4.2.4 Apparatus**

During the experiment participants' eye movements were recorded at a sampling rate of 250Hz with the SR-Research EyeLink II, which has an average spatial resolution of  $< 0.005^\circ$ . Only the dominant eye was tracked. Stimuli were presented across three Samsung monitors, each with a screen resolution of 1920 by 1080 pixels, an aspect ratio of 16:9, a width of 88.6cm, and a height of 49.8cm. The left and right screens were placed at  $120^\circ$  to each other. Participants were seated at a distance of 100cm (setup shown in Figure, 4.2a). The screens had a combined horizontal viewing angle of  $180^\circ$  and a vertical viewing angle of  $32^\circ$ . The experiment was coded in Worldviz Vizard 5.0 using Python 2.7 and the PyLink Toolbox extensions (Peirce, 2007). Calibrations for eye fixations were conducted at the beginning of the experiment using a nine-point fixation procedure as implemented in the EyeLink API (see EyeLink Manual). Calibrations were then validated with EyeLink software

and repeated until there was less than  $1^\circ$  of error for every calibration point. Head position and orientation were recorded using the Polhemus Fastrak motion tracking system with a sampling rate of 120Hz.

#### 4.2.5 Experimental Procedure

Both experiments used a virtual road crossing environment created in 3DS Max and Maya (Figure. 4.2b) which was made to simulate the road crossing scene used in Nicholls et al. (2019) and Chapter 3, without the roundabout. Prior to the start of the experiment participants' eye movements were calibrated using a custom calibration procedure across all three screens. This procedure involved presenting circles with a break on the left or right side and a dot in the middle (Figure 4.1) at random locations on all three screens. Participants had to look at the circle and indicate whether the break in the circle was on the right or left hand side using the left and right arrow keys on the keyboard. While participants performed this task their eye movements were recorded. Once this was completed participants eye movements were calibrated on one screen using the Eyelink calibration procedure.

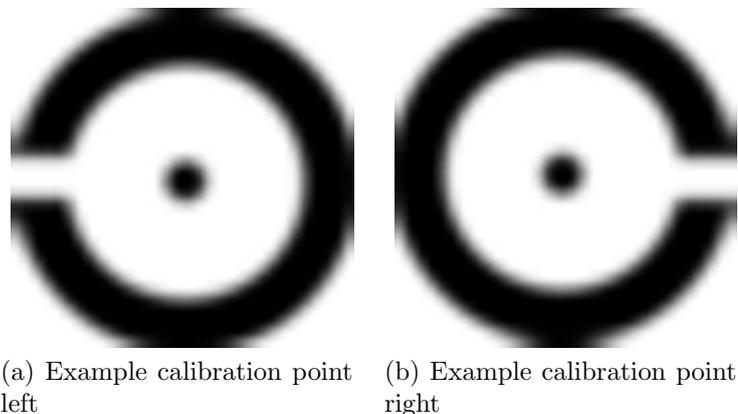
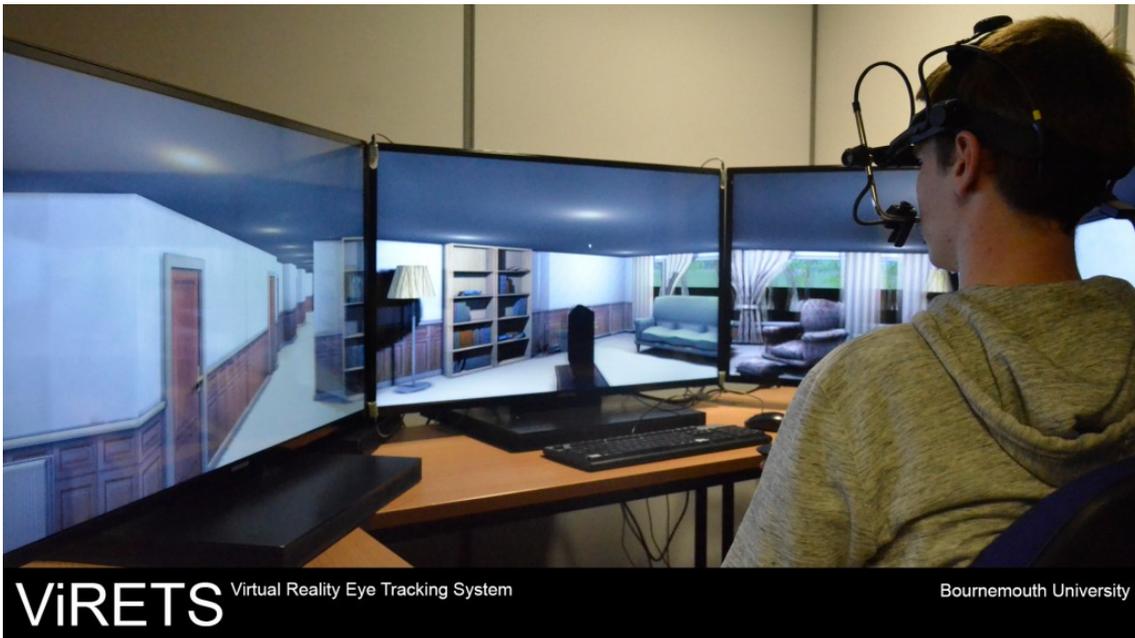


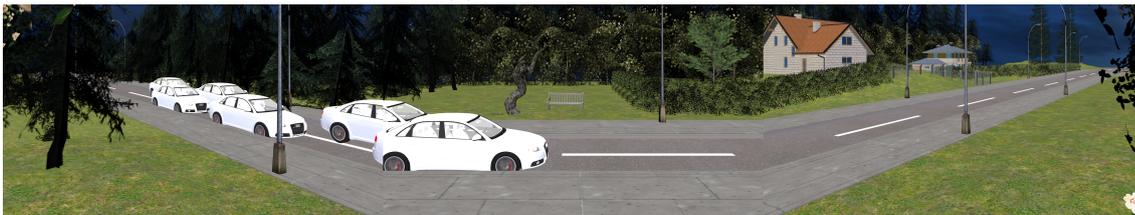
Figure 4.1: Example calibration points for the three screen calibration of the Eyelink II. (a) Example calibration point with the break in the circle on the left. (b) Example calibration point with the break in the circle on the right

At the beginning of the experiment participants were informed that they would be presented with a series of road crossing situations on screen and that they would have to indicate by pressing the spacebar on a keyboard when they could cross the road and hold the key pressed for as long as they thought it was safe to cross. At the start of each experimental block participants were informed on which side the cars

would appear from – left hand side, right hand side, or both sides (Experiment 2 only). Vehicles travelled at two speeds – 249 (slow) or 583 (fast) virtual world units per second. This was equivalent to approximately 30 and 70 km/h respectively. Each trial started with the presentation of a central fixation cross. Once the participants had fixated on the cross, the virtual environment was presented. Each trial was followed by a black screen with text stating the trial had ended and the participant should press the spacebar to continue. Once the participants pressed the spacebar the next trial would start with the central fixation cross.



(a) Experiment setup



(b) Experiment stimulus



(c) Time to impact explanation

Figure 4.2: VR experiment set up and stimulus

## 4.2.6 Statistical analyses

All statistical analyses and figures were created and performed using Matlab 2019a (MATLAB, 2019) and R version 3.6.3 (R Core Team, 2020).

### Crossing decisions

I defined “time to impact” (TTI) as the time that it would take for the closest approaching vehicle, in each lane, to reach the participants, from the moment when the participants stopped indicating that crossing was safe (i.e. when they released the spacebar indicating that it was no longer safe to cross). This is illustrated in Figure 4.2c. Previously, it has been shown that YAs and OAs are able to make decisions based on a combination of time and distance to impact (DTI; Lobjois & Cavallo, 2007). As cars were moving at a constant speed with equally sized gaps between the cars, I was not able to investigate this as the DTI was perfectly correlated with the TTI (Figure C.1). To investigate DTI alongside TTI, I could have had cars with different sized gaps between them, moving with changing speeds, or accelerations.

The crossing decisions in both experiments were analysed with linear mixed models (LMMs). In Experiment 1 the model included fixed effects of age group (above or below 60y/o), number of lanes, near or far lane, car speed, car direction, direction of travel (from the left or right), RMA RTs, zoo map score, global switch cost on RMA RTs, local switch cost on RMA RTs. The model included interactions between age and each of the task conditions. There were also interactions between each of the executive functioning measures and each of the task conditions. The model also included random intercepts for each participant and each trial. To begin with, the model contained random slopes for each fixed factor but the model did not converge so all random slopes were removed.

In Experiment 2 the model included fixed effects of age group (above or below 60y/o), traffic density, presence of distractors, car speed, direction of travel (from the left, right, or both directions), RMA RTs, zoo map score, global switch cost on RMA RTs, local switch cost on RMA RTs. The model included interactions between

age and each of the task conditions. There were also interactions between each of the executive functioning measures and each of the task conditions. The model also included random intercepts for each participant and each trial. To begin with, the model contained random slopes for each fixed factor but the model did not converge so all random slopes were removed. This model initially included interactions for cars appearing from both directions and car speed, cars appearing from an obscured viewpoint, traffic density, and pedestrian presence. This model did not converge so these interactions were removed. To keep the current chapter concise I focused on the fixed effects that answered my main hypotheses in the results sections for Experiment 1 and Experiment 2. As the fixed effect of RMA RT was an additional exploratory analysis the results for this effect can be found in Appendix C.

For both experiments LMMs were performed for the number, and duration of button presses, and the TTI. All significant interaction produced by these LMMs were investigated using simple effects LMMs with a Tukey HSD correction for multiple comparisons.

### **Executive function tests**

Differences between older and younger adults on all measures were determined using a bootstrap t-test with 20% trimmed means. Multiple comparisons were corrected using the Hochberg method. I used bootstrap t-tests as they handle skewed distributions and outliers better than the Student's t-test (Rousselet et al., 2019). Bayes factors were also calculated using the BayesFactor package in R (Morey & Rouder, 2018), after outliers were removed using the median absolute deviation (MAD) rule.

### **Eye movements**

The eye movement analyses are not available at this point in time. My projection of eye positions in the 4D virtual space and time was much more challenging than expected. The Eyelink II is set up to be used for one screen, so gaze coordinates can only be determined for one screen. To use a three screen set up one needs to use head motion and position data measured by a separate motion tracker. One also needs to use the head referenced position data (HREF). HREF measures eye

rotation angles relative to the head. However, the output data is not a rotation angle of the eye but x and y coordinates which define a point on the HREF plane which is a constant 15,000 units away from the participant. The eye rotation angle can then be determined from the coordinates using the following equation provided in the Eyelink II manual:

$$\text{angle} = \text{acos}( (f*f + x1*x2 + y1*y2) / (\text{sqrt}( (f*f + x1*x1 + y1*y1) * (f*f + x2*x2 + y2*y2) ) ) );$$

f is the constant distance from the participants' eyes to the HREF plane, and x and y are the HREF x and y coordinate values. During the calibration the HREF values were scaled and from there you can related the HREF coordinates to real world coordinates. A new calibration procedure was required to ensure that the HREF values are scaled appropriately for the three screen environment I used. A member of my supervisory team had managed to develop a calibration procedure for three screens, as mentioned in the experimental procedure subsection, but we had not yet developed a way to scale the HREF coordinates after the calibration procedure was completed. The supervisory team, in collaboration with international experts, is currently working on tackling this challenge and offering flexible and robust open source solutions to the vision science community. To give an idea of how much participants shifted their attention I analysed the amount head movements participants made.

### **Head movements**

I analysed head movements by summing the change in angle of the head between each sample recorded on the trial. The summed head movements were then analysed with LMMs using the same models as those used for the crossing decisions for both experiments. As these analyses were additional exploratory analyses the results can be found in Appendix C.

## 4.2.7 Experiment Design

In this experiment 30 trials were presented to participants, split into two blocks of 15 trials. Each trial lasted 15 seconds. For one block the cars travelled from left to right, and on the other cars travelled from right to left. The view of the cars that travelled from left to right were slightly obscured by trees (Figure 4.2b). The view of the cars that travelled from right to left was not obstructed. On each trial two cars were presented. For half the trials both cars travelled along one lane, either the near or the far lane. For the other half of the trials the cars travelled in both lanes but in the same direction. Four different car models were presented randomly – Audi S4, Toyota Prius, Volkswagen Polo, and Volkswagen Beetle. All car models were coloured white, except for the Polo that was coloured red. All cars in a given trial were of the same model. The speed of the cars was randomly set to either 30 or 70km/h but all cars presented on a given trial moved at the same speed. A summary of the conditions are presented in Figure 4.3 with the exception of car speed and car model.

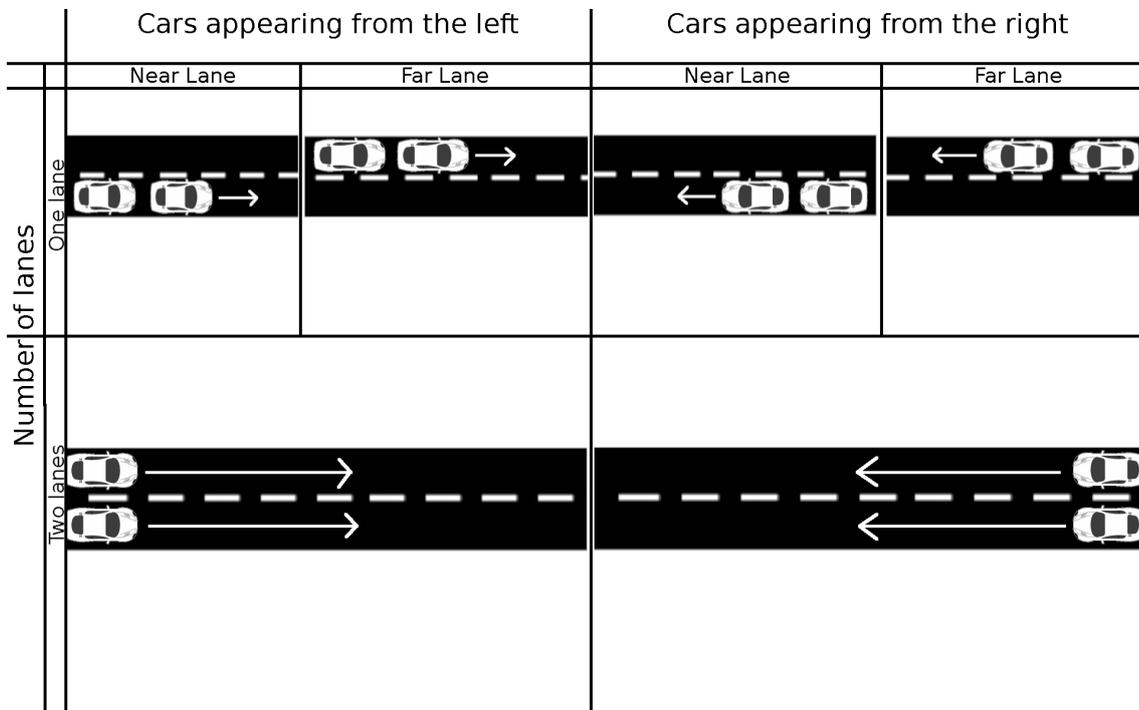


Figure 4.3: Conditions for Experiment 1

### 4.3 Results – Executive function tests

Bootstrap t-tests and Bayes factors indicated that OAs and YAs had similar walking speeds (Table 4.1, Figure 4.4H), accuracy in the RMA task (Table 4.1, Figure 4.4A), local and global switch costs on RMA task accuracy (Table 4.1, Figure 4.4C, and E respectively), and BADS zoo map scores (Table 4.1, Figure 4.4G). Older adults showed significantly longer response times on the RMA task than YAs (Table 4.1, Figure 4.4B), as well as larger local and global switch costs on their RMA RTs than YAs (Table 4.1, Figure 4.4D, and F respectively).

Table 4.1: Means, bootstrap t-tests and Bayes Factors for the differences between OAs and YAs for the different executive function measures, testing attention switching ability (local and global switch costs and RMA performance), spatial planning ability (BADS zoo map test), and walking speed. Significant results are highlighted in blue.

	<i>Means</i>	<i>t-value</i>	<i>df</i>	<i>CI</i> s	<i>p-value</i>	<i>d</i>	<i>Bayes Factor</i>
Walk speed	YA:1.33, OA:1.37	0.12	17.51	[-0.10, 0.12]	0.903	0.08	0.37
RMA score	YA:0.95, OA:0.94	-0.44	11.34	[-0.07, 0.05]	0.670	0.15	0.30
Local switch cost on RMA score	YA:0.04, OA:0.05	0.47	12.53	[-0.03, 0.41]	0.684	0.13	0.31
Global switch cost on RMA score	YA:0.03, OA:0.03	-0.65	24.87	[-0.02, 0.01]	0.505	0.20	0.30
BADS zoo map score	YA:3.10, OA:2.63	-1.68	12.25	[-1.77, 0.16]	0.099	0.42	1.63
RMA RT	YA:1.42, OA:1.93	3.05	17.36	[0.17, 0.85]	0.005	0.64	27.29
Local switch cost on RMA RT	YA:0.23, OA:0.38	2.68	10.79	[0.03, 0.34]	0.022	0.56	2.25
Global switch cost on RMA RT	YA:0.40, OA:0.94	2.98	14.39	[0.14, 0.74]	0.008	0.70	18.17

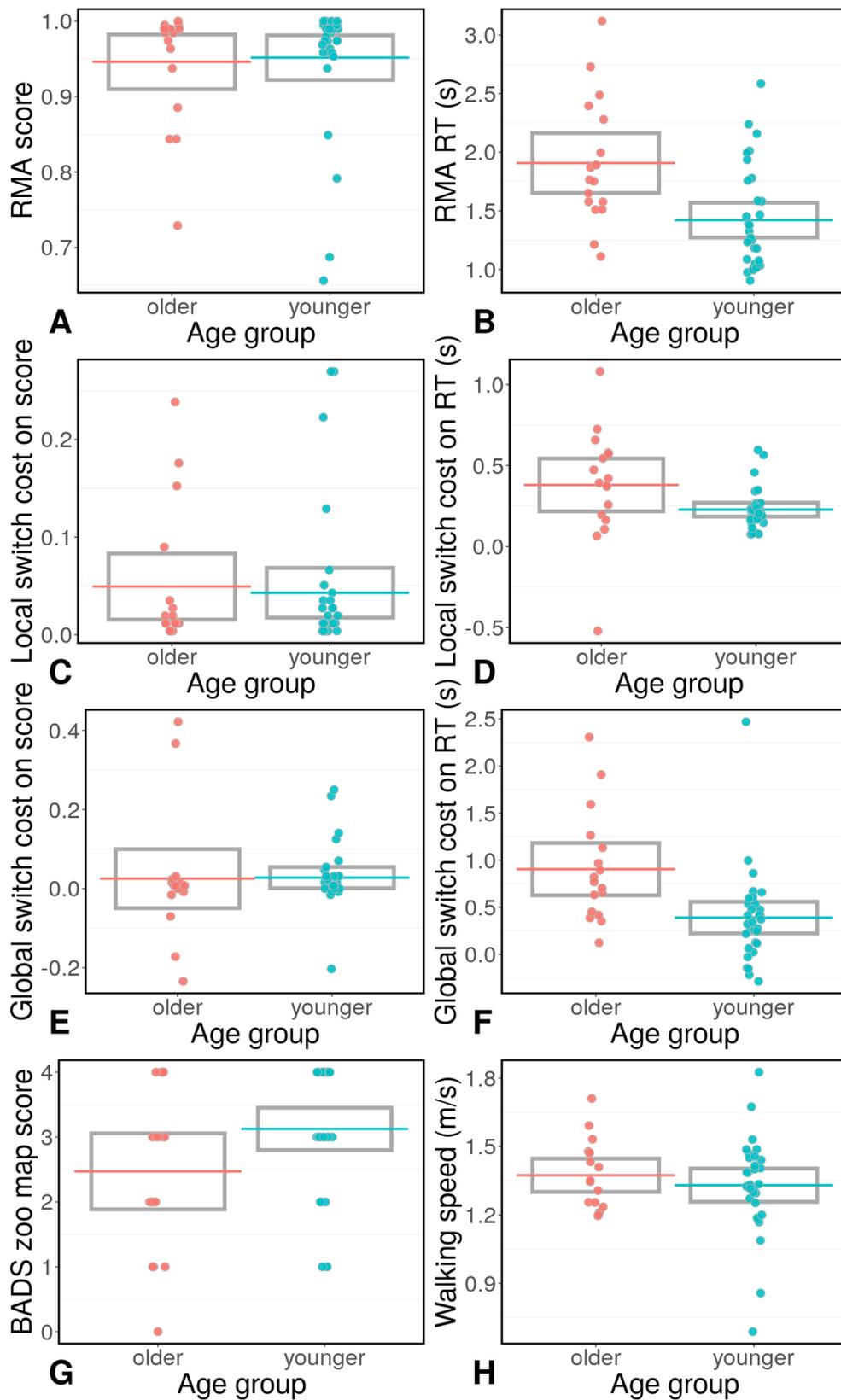


Figure 4.4: Executive function results. Participants' accuracy (A) and RTs (B) on the RMA task. Local switch costs on RMA task accuracy (C) and RT (D). Global switch costs on RMA task accuracy (E), and RT (F). Participants' BADS zoo map scores (G). Participants' walking speed (H). In all panels the red colours indicate OAs and blue colours indicate YAs.

## 4.4 Results – Experiment 1

### 4.4.1 Impact of car speed on crossing behaviour

There were main effects of car speed on the number of crossing decisions and TTI (number of crossing decisions:  $\beta=0.39$ ,  $SE=0.17$ ,  $t=2.32$ ,  $p=0.020$ , Table C.1; TTI:  $\beta=-1.17$ ,  $SE=0.53$ ,  $t=-2.19$ ,  $p=0.029$ , Table C.27). All participants made more crossing decisions, and had shorter TTI when cars travelled faster compared to slower. This reduction in TTI was larger for OAs, and participants with lower BADS zoo map scores (Table C.27-C.31; Figure 4.5B and A respectively).

The LMM performed on the duration of key presses showed interactions between age and car speed, as well as spatial planning ability and car speed (age:  $\beta=-1.16$ ,  $SE=0.35$ ,  $t=-3.37$ ,  $p=0.001$ ; BADS:  $\beta=-0.53$ ,  $SE=0.15$ ,  $t=-3.36$ ,  $p=0.000$ , Table C.2). OAs made longer key presses when cars travelled quickly compared to slowly (Table C.4, Figure C.4C). YAs made shorter key presses when cars travelled quickly compared to slowly (Table C.3, Figure C.4C). Participants with higher BADS zoo map scores made shorter key presses when cars moved faster compared to when cars moved slower (Table C.5, Figure C.4D). Participants with low BADS zoo map scores made longer key presses when cars travelled faster than when cars travelled slower (Table C.6, Figure C.4D).

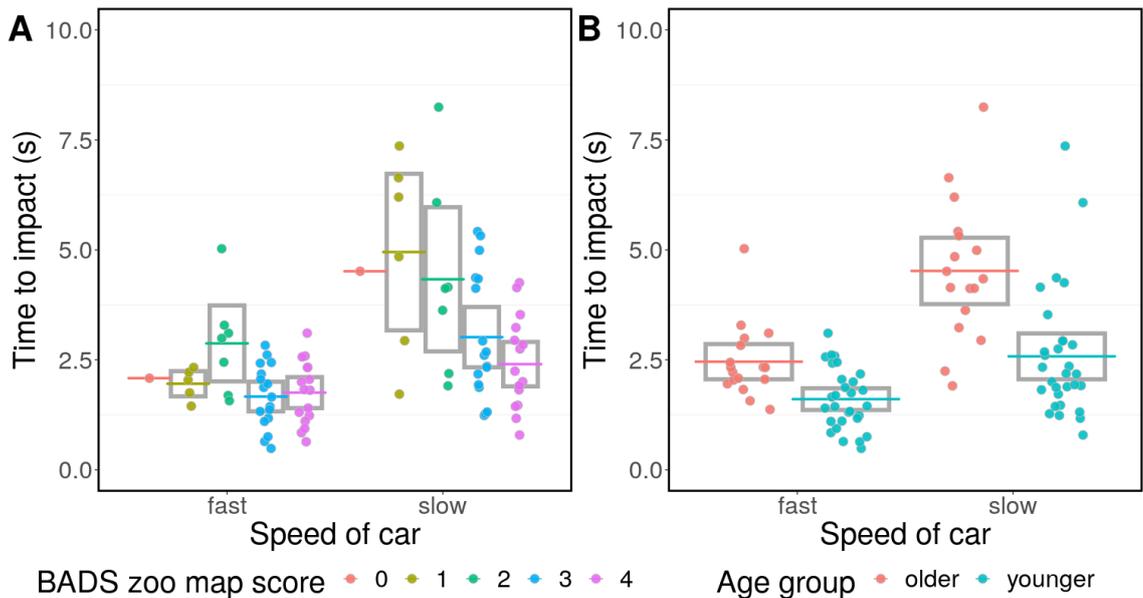


Figure 4.5: The effect of car speed on TTI for OAs and YAs (B), and for participants with low and participants with high BADS zoo map scores (A).

#### 4.4.2 Impacts of cars coming from an obscured view

The LMMs showed a main effect of cars appearing from an obscured view on the number of crossing decisions, and TTI (number of crossing decisions:  $\beta=-0.45$ ,  $SE=0.17$ ,  $t=-2.72$ ,  $p=0.007$ , Table C.1; TTI:  $\beta=-1.85$ ,  $SE=0.52$ ,  $t=-3.53$ ,  $p=0.000$ , Table C.27). All participants decreased their number of crossing decisions and TTI. This decrease in TTI was greater for OAs than YAs, and greater for participants with low BADS zoo map scores than participants with high BADS zoo map scores (Table C.27-C.31; Figure 4.6).

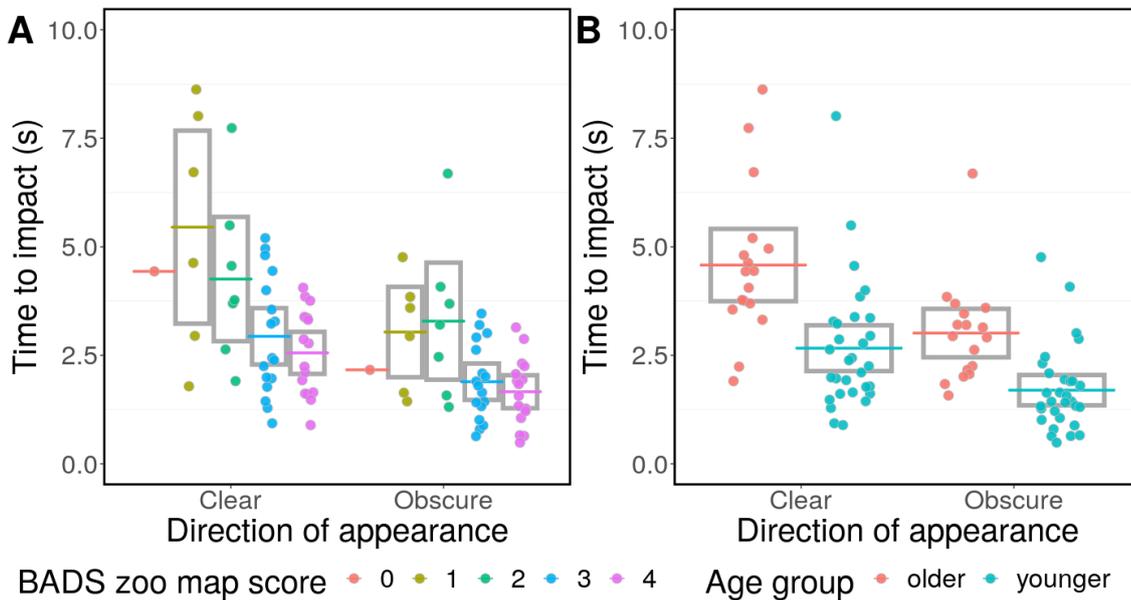


Figure 4.6: The effect of cars coming from an obscured view on the TTI for OAs and YAs (B), and participants with high and low BADS zoo map scores (A)

#### 4.4.3 Number of lanes

There were no significant effects of cars coming from two lanes compared to one lane. For a summary of these results see Tables C.1, C.2, and C.27 in Appendix C.

#### 4.4.4 Near or far lane

There were no significant effects of which lane the cars travelled in. For a summary of these results see Tables C.1, C.2, and C.27 in Appendix C.

## **4.5 Discussion – Experiment 1**

### **4.5.1 Do OAs and participants with poorer executive functioning abilities show riskier crossing behaviour when task complexity is increased?**

The results from Experiment 1 reveal that all participants show riskier crossing behaviour when task complexity is increased, as participants reduced their TTI when task complexity increased. I consider a reduction in TTI to be risky as for all participants as decreasing their TTI would leave participants less time to cross at a real road crossing. The impact of increased task complexity was greater for OAs and participants with poorer executive functioning abilities than YAs and participants with better executive functioning abilities. The increase in risky crossing behaviour did not occur for all conditions. The increase in risky crossing behaviour occurred when cars travelled quickly, and when the viewpoint of the cars was obscured. The increase did not occur when cars travelled in the far lane or both lanes simultaneously.

### **4.5.2 Conditions that impact negatively on crossing behaviour**

When cars came from an obscured viewpoint, the cars were closer to participants when they became visible, leaving participants less time to make a decision on whether they could cross safely. Similarly, when cars travel faster this leaves participants less time to make a decision on whether they should cross safely. Therefore, the vehicles in both conditions would have been closer to the participants when they made their crossing decision, resulting in a reduction in their TTI. The reason OAs may have been more impacted by cars travelling quickly or from an obscured viewpoint than YAs is that OAs had longer RTs than YAs. This was determined from the RMA task where OAs had longer RTs than YAs across the whole task. Therefore, a larger reduction in TTI compared to YAs may be due to OAs reacting slower than YAs. This behaviour would be risky as OAs are not able to properly take into account their slower RTs in difficult situations such as when cars come

from an obscured view or travelled quickly. Further research should be done to determine how aware OAs are of their declining mental and physical functioning and if they attempt to account for these in their everyday decisions.

An alternate explanation for the larger reduction in TTI for OAs may be because OAs have slower visual processing than YAs (Bock et al., 2015; Di Fabio et al., 2003, 2005; Ritchie, Tucker-Drob, & Deary, 2014; Salthouse, 1996). If OAs have slower processing speeds then they might need to look at cars for longer to determine their speed and an appropriate TTI. Therefore, when cars travel quickly, or from an obscured viewpoint the cars would be closer to the participants when they released the button leading to a shorter TTI compared to when cars travel slowly or from a clear viewpoint.

Even though OAs were more impacted by cars coming from an obscured view and cars travelling quickly, in that they reduced their TTI in both conditions, they still left more TTI than YAs in all situations. Moreover, YAs also reduced their TTI when cars travel quickly or come from an obscured view. This reduction in TTI suggests that YAs also have difficulties in these situations and these may be the sorts of situations that lead to YAs being involved in pedestrian accidents. More research should be done to determine which situations not only children and OAs have accidents in but YAs as well, and as a result what infrastructure or training methods can be developed to improve the safety of all road users.

Similarly to OAs, participants with poorer executive functioning abilities, specifically spatial planning abilities showed a greater reduction in TTI than participants with better spatial planning abilities. This suggests participants with poorer spatial planning abilities were more impacted by cars travelling quickly or coming from an obscured view than participants with better spatial planning abilities. Participants with poorer spatial planning might have been more impacted than participants with better spatial planning abilities in the obscured view and fast car conditions because they are less efficient at executing a plan than participants with better spatial planning abilities (Allain et al., 2005; Shallice, 1982). As they are less efficient at executing the planned action they may not release the button as early as partici-

pants with better spatial planning abilities, causing participants with poorer spatial planning abilities to reduce their TTI by more than participants with better spatial planning abilities. Even though the reduction in TTI was greater for participants with poorer spatial planning abilities than participants with better spatial planning abilities, they still left more TTI than participants with better spatial planning abilities. This suggests that although participants with poorer spatial planning abilities were more impacted it was not to the extent where they made riskier crossing decisions than participants with better spatial planning abilities. In a more complex task such as cars travelling from both an obscured direction and a clear direction at the same, where there are more cars to take into account when planning a crossing decision, participants with poorer spatial planning abilities might start to make riskier crossing decisions than participants with better spatial planning abilities.

### **4.5.3 Conditions that did not impact on crossing behaviour**

Increasing task complexity through cars travelling from the far lane or both lanes did not impact on participants' crossing behaviour. If the participants had a more risky strategy when cars travelled in the far lane or on both lanes I would expect them to make more crossing decisions or leave less TTI. However, participants did not change their crossing behaviour when cars travelled in the far lane or on both lanes. Therefore, it seems that all participants are able to make as safe crossing decisions in these situations as in less complex situations such as cars travelling in one lane or the close lane only.

These results contrast to previous findings that OAs make more errors when cars travel in the far lane (Dommès, Cavallo, Dubuisson, Tournier, & Vienne, 2014; Geraghty et al., 2016; Oxley et al., 1997). The previous findings that OAs make more errors in the far lane may, therefore, result from keeping track of cars coming from both directions rather than the number or type of lane.

When cars travel in the far lane or in both lanes the time participants have to determine a safe TTI is not reduced, therefore leaving participants with enough time to determine the TTI they require to cross. The amount of objects that participants

have to keep track of also does not change so the complexity of the task in these two conditions is not increased. In conditions where there are more cars, cars travel from both directions, or pedestrian distractors are present may provide more difficulty for participants by increasing the amount of information participants need to hold in their working memory. For example, when cars travel in both directions and both lanes participants need to initially look towards one side of the road, take in the position of the cars, make an estimate of their speed so they can predict when the cars would reach the participants' position. All this information has to be taken in and held in the memory while participants look to the other side of the road and make the same judgements about the cars coming from the left. Participants then also need to plan when they would cross the road. Given OAs typically show a decline in working memory capacity (Bopp & Verhaeghen, 2005; Schneider-Garces et al., 2010) and planning abilities (Phillips, Gilhooly, Logie, Sala, & Wynn, 2003) they may find it difficult to hold the necessary amount of information and plan out the cars' trajectories when cars travel from both directions, while ignoring pedestrian distractors. Therefore, OAs might have a particular challenge with making crossing decisions when there are more objects to keep track of in a scene such as when cars travel from both directions, traffic density is high or pedestrian distractors are present. I investigated the impact of each of these three conditions in Experiment 2.

#### **4.5.4 Summary Experiment 1**

In sum, I added to the results in Chapter 3 by investigating the impact of task complexity on crossing decisions. I found that all participants have difficulties when task complexity is increased by cars travelling quickly or from an obscured viewpoint as all participants reduced their TTI. I also found that participants were not impacted by increasing the task complexity through cars travelling in the far lane or travelling in both lanes.

## 4.6 Introduction – Experiment 2

In Chapter 3 and in Experiment 1 of this chapter I find that OAs are able to make safe crossing decisions with cars travelling from one direction, irrelevant of whether the cars travel in the near or far lane, or in both lanes. In Chapter 3 I suggested that OAs may have difficulties when the complexity of the task is increased by having cars travel along two directions. Indeed, OAs have previously been shown to make riskier crossing decisions when cars came from two directions (Dommes et al., 2013; Geraghty et al., 2016; Oxley et al., 1997, 2005).

OAs have also been shown to not be as able as YAs at tracking objects when their attention is divided between multiple objects, especially when these objects travel quickly (Sekuler, McLaughlin, & Yotsumoto, 2008; Tsang, 1998; Trick, Jaspers-Fayer, & Sethi, 2005). In road crossing situations there are often varying levels of traffic and distractors such as other pedestrians that individuals have to keep track of or ignore. Even though I find no effect of traffic density on crossing decisions, and eye movement behaviour in Chapter 3, the combination of having to divide attention between cars coming from both directions quickly, and with many cars on the road, OAs may find it more difficult to continue to make safe crossing decisions. In Chapter 3 I found that OAs attention was captured by pedestrian distractors but this was not associated with riskier crossing decisions. Pedestrian distractors may have more of an influence when cars come from both directions as OAs attention will be split between the pedestrian distractors and attending to cars coming from multiple directions, rather than cars just coming from one direction.

In this experiment I assessed the influence of cars travelling from both lanes, cars travelling quickly, traffic density, and the presence of pedestrian distractors on the visual attentional control and the crossing behaviour of OAs and participants with reduced executive functioning abilities. I used the same VR set up as in Experiment 1, but in this experiment cars always travelled along both lanes and I manipulated the car speed, cars travelling from one side or both sides of the road, cars travelling from an obscured or non-obscured viewpoint, traffic density, and the presence of task-irrelevant pedestrian distractors.

As with Experiment 1 the overarching research question was: Do OAs and participants with better executive functioning abilities show riskier crossing behaviour when task complexity is increased than YAs and participants with better executive functioning abilities?

In this experiment I increase task complexity in the following ways:

- Increasing car speed.
- Cars travelling from both the left and right hand sides of the participants.
- Obscuring the viewpoint of the cars.
- Increasing traffic density.
- Having pedestrian distractors present.

## 4.7 Methods – Experiment 2

All participants, apparatus, and the experimental procedure was the same as in Experiment 1. The statistical analysis is in the Methods for Experiment 1.

### 4.7.1 Experimental Design

In this experiment 120 trials were presented to participants, split into three blocks of 40 trials, each trial lasted for 15 seconds. On each trial cars travelled along both lanes, the car travel direction was different for each block and the order was altered for each participant. On one block cars travelled from left to right, another from right to left, and one from both directions. The view of the cars that travelled from left to right were slightly obscured by trees. The view of the cars that travelled from right to left was not obstructed. The number of cars presented on each trial varied between two, four, and six cars. On half the trials in each block the car speed was fast (70 km/h) and on the other half the car speed was slow (30 km/h). All cars presented in a trial travelled at the same speed. In half the trials in each block pedestrian avatars were present that walked along the near or far sidewalk, or stood still. The number of pedestrians presented on the trials varied randomly between

one and two pedestrians. The same four car models as in Experiment 1 were used in this experiment and were also randomly varied. A summary of the conditions are presented in Figure 4.7 with the exception of car speed.

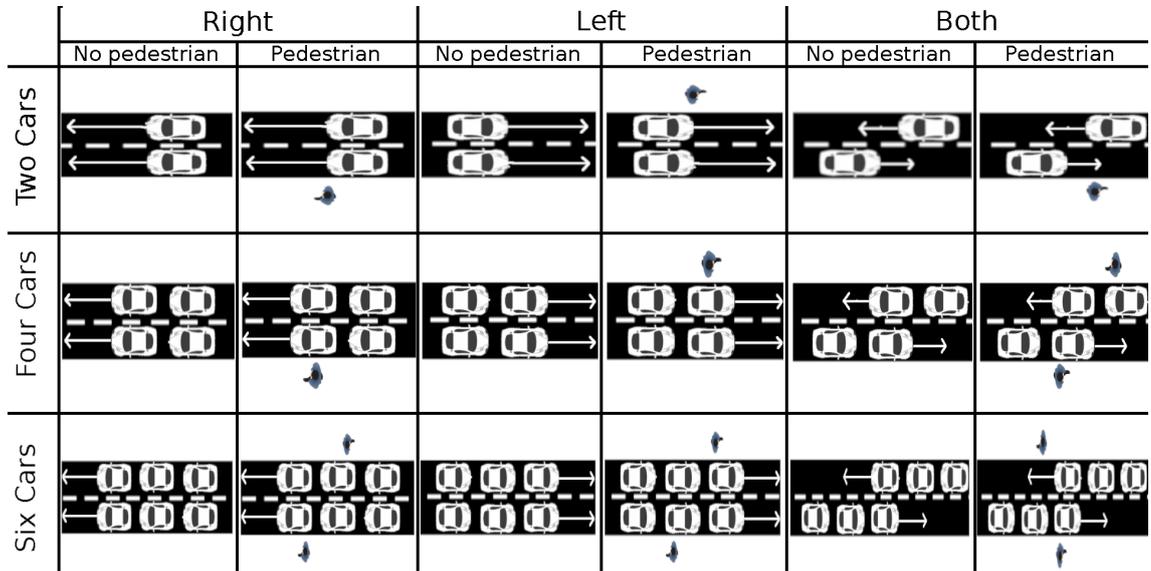


Figure 4.7: Conditions for Experiment 2

## 4.8 Results – Experiment 2

### 4.8.1 Impacts of car speed on crossing behaviour

There were main effects of car speed on the number of crossing decisions, duration of key presses, and TTI (number of crossing decisions:  $\beta=0.34$ ,  $SE=0.10$ ,  $t=3.44$ ,  $p=0.001$ , Table C.7; duration of key presses:  $\beta=3.57$ ,  $SE=0.48$ ,  $t=7.37$ ,  $p=0.000$ , Table C.18; TTI:  $\beta=-2.32$ ,  $SE=0.36$ ,  $t=-6.92$ ,  $p=0.000$ , Table C.34). All participants made more crossing decisions, had shorter TTI, and had longer key presses when cars travelled quickly compared to slowly. The decrease in TTI was larger for OAs than YAs, and for participants with lower BADS zoo map scores than participants with higher BADS zoo map scores (Tables C.36, C.35, C.40, and C.39; Figures 4.8B, and D). The increase in the duration of key presses was greater for OAs than YAs, and for participants with larger switch costs (global and local) than participants with smaller switch costs on the RMA task (Tables C.19-C.26; Figures C.8B, E, and F).

The LMM on the number of crossing decisions showed an interaction between age

group and car speed, between spatial planning ability and car speed, and between attention switching ability and car speed (age group:  $\beta=-0.08$ ,  $SE=0.04$ ,  $t=-2.18$ ,  $p=0.029$ ; BADS:  $\beta=-0.07$ ,  $SE=0.02$ ,  $t=-4.42$ ,  $p=0.000$ ; attention switching:  $\beta=-0.29$ ,  $SE=0.07$ ,  $t=-3.85$ ,  $p=0.000$ , Table C.7). YAs decreased their number of crossing decisions but OAs did not significantly change their number of crossing decisions when cars travelled quickly compared to slowly (Tables C.9, and C.8; Figure 4.8A). Participants with high BADS zoo map scores decreased their number of crossing decisions while participants with low BADS zoo map scores did not significantly change their number of crossing decisions (Tables C.12, and C.13; Figure 4.8C). Participants with larger and participants with smaller local switch costs increased their number of crossing decisions when cars travelled quickly compared to slowly (Figure 4.8E). This increase was larger for participants with larger local switch costs than participants with smaller local switch costs on the RMA task (Tables C.16, and C.17).

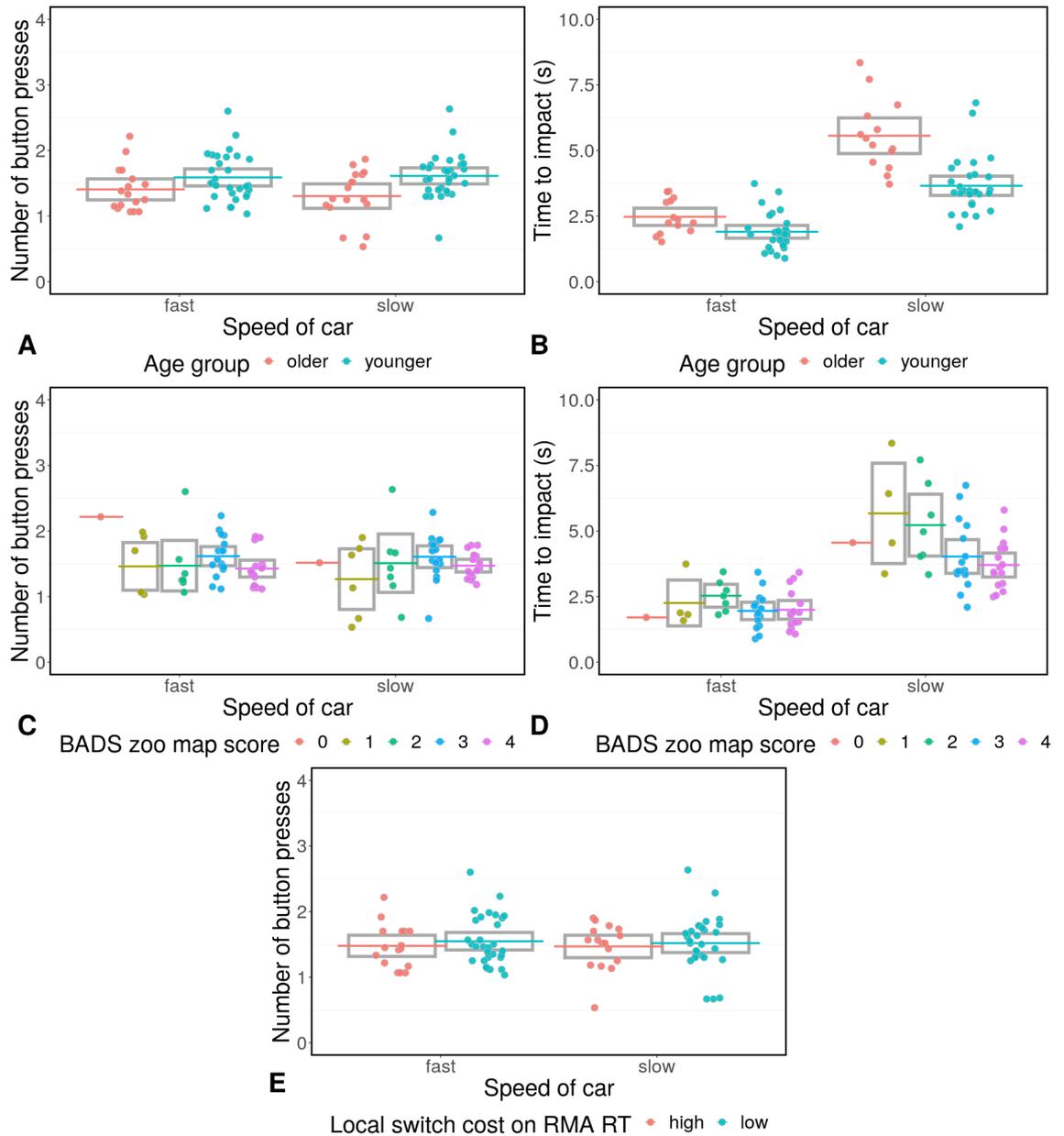


Figure 4.8: The effect of car speed on the number of crossing decisions (A), and TTI (B) for OAs and YAs. The effect of car speed on number of crossing decisions (C), and TTI (D) for participants with low and participants with high scores on the BADS zoo map test. The effect of car speed on the number of crossing decisions (E) for participants with large and small local switch costs on the RMA task.

#### 4.8.2 Impact of cars coming from both directions on crossing behaviour

The LMMs showed main effects of travel direction on the number of crossing decisions participants made ( $\beta=0.37$ ,  $SE=0.12$ ,  $t=3.03$ ,  $p=0.002$ , Table C.7). All participants made more crossing decisions when cars came from both directions

compared to just one direction. The difference in the number of crossing decisions was greater for participants with higher BADS zoo map scores than participants with lower scores (Table C.12 and C.13; Figure 4.9C). The LMMs showed an interaction between age group and travel direction on the number of crossing decisions made ( $\beta=0.34$ ,  $SE=0.05$ ,  $t=7.32$ ,  $p=0.000$ , Table C.7). YAs increased their number of crossing decisions while OAs did not significantly change their number of crossing decisions (Tables C.8, and C.9 Figure 4.9A).

The LMM on TTI showed an interaction between age group and car travel direction, between spatial planning ability and car travel direction, and between attention switching ability and car travel direction (age group:  $\beta=-0.55$ ,  $SE=0.17$ ,  $t=-3.33$ ,  $p=0.0001$ ; BADS:  $\beta=0.15$ ,  $SE=0.06$ ,  $t=2.43$ ,  $p=0.015$ ; attention switching:  $\beta=1.85$ ,  $SE=0.37$ ,  $t=4.98$ ,  $p=0.000$ , Table C.34). All participants had longer TTI when cars travelled from both directions compared to just one direction. The differences were greater for YAs than OAs, for participants with higher BADS zoo map scores than participants with lower scores, and for participants with larger local switch costs than participants with smaller local switch costs on the RMA task (Table C.34-C.40, Figures 4.9B, D, and E).

The LMMs also showed an interaction between age group and car travel direction on the duration of key presses ( $\beta=-1.18$ ,  $SE=0.23$ ,  $t=-5.21$ ,  $p=0.000$ , Table C.18). OAs and YAs both made shorter key presses when cars travelled from both directions compared to one direction. This difference in key press duration was greater for YAs than OAs (Tables C.19, and C.20; Figure C.8C).

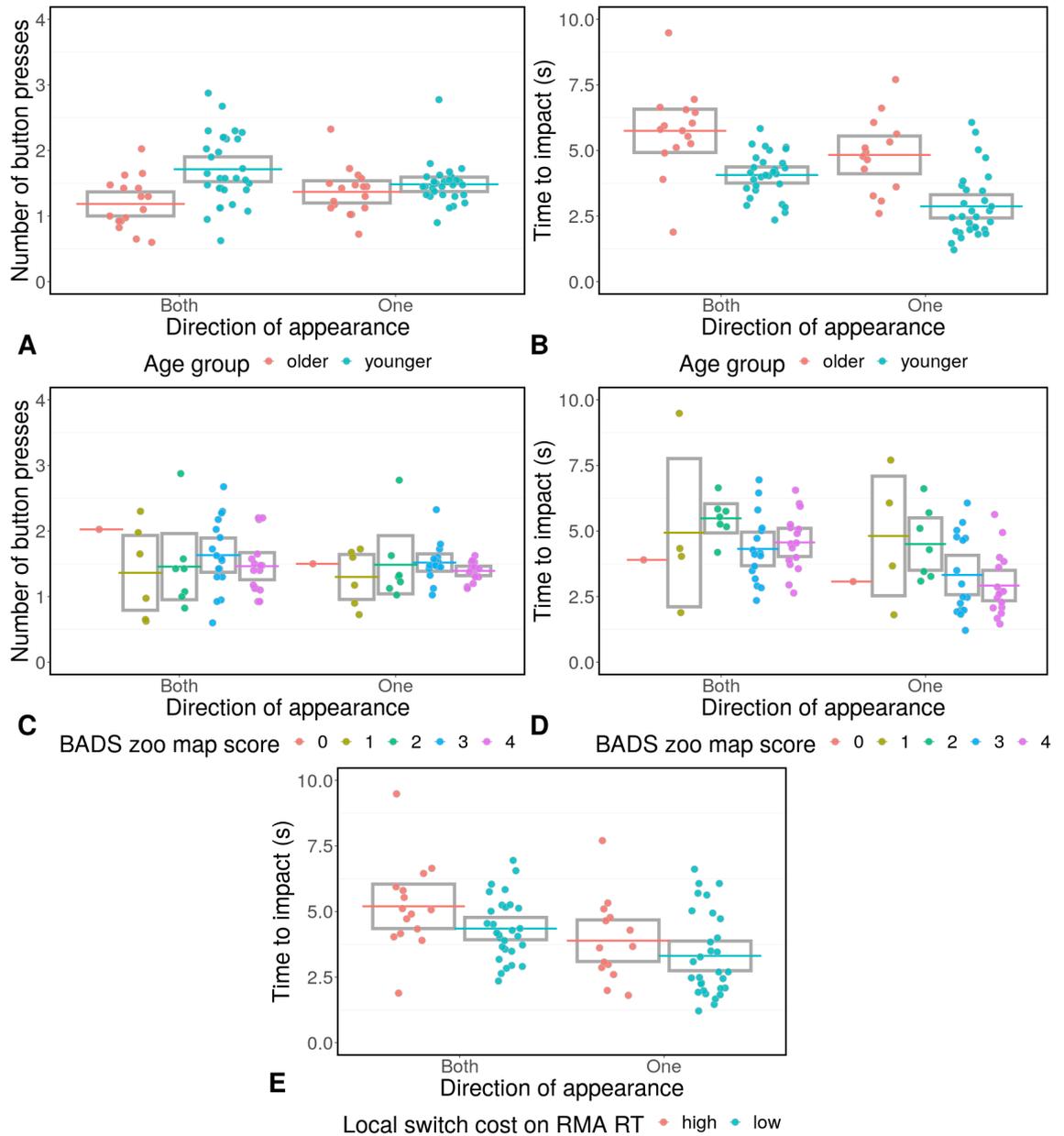


Figure 4.9: The effect of cars coming from both directions on the number of crossing decisions, and TTI for OAs and YAs (A,B); participants with low and high BADS zoo map scores (C,D). The effect of cars coming from both directions on TTI for participants with small and large local switch costs on the RMA task (E).

### 4.8.3 Impact of cars coming from an obscured view on crossing behaviour

The LMMs showed main effects of travel direction on the duration of key presses and TTI (duration of key presses:  $\beta=1.83$ ,  $SE=0.59$ ,  $t=3.13$ ,  $p=0.002$ , Table C.18; TTI:  $\beta=-1.70$ ,  $SE=0.39$ ,  $t=-4.32$ ,  $p=0.000$ , Table C.34). All participants increased their duration of key presses and decreased their TTI when cars travelled from an

obscured view compared to a clear view. The decrease in TTI was greater for OAs than YAs and for participants with larger local switch costs than participants with smaller local switch costs on the RMA task (Tables C.35-C.38; Figures 4.10A, and B). The LMMs on key press duration showed an interaction between travel direction and age group ( $\beta=-0.73$ ,  $SE=0.22$ ,  $t=-3.32$ ,  $p=0.001$ , Table C.18). OAs increased their key press duration when cars travelled from an obscured viewpoint compared to a clear one (Table C.20, Figure C.8D). YAs did not significantly change their key press duration when cars travelled from an obscured viewpoint compared to a clear one (Tables C.19, Figure C.8D).

The LMM on the number of crossing decisions showed an interaction between attention switching ability and travel direction ( $\beta=-0.11$ ,  $SE=0.05$ ,  $t=-2.13$ ,  $p=0.033$ , Table C.7). Participants with smaller global switch costs increased their number of crossing decisions when cars travelled from an obscured viewpoint compared to a clear one (Table C.15, Figure 4.10C). Participants with larger global switch costs did not significantly change their number of crossing decisions when cars travelled from an obscured viewpoint compared to a clear one (Table C.14, Figure 4.10C).

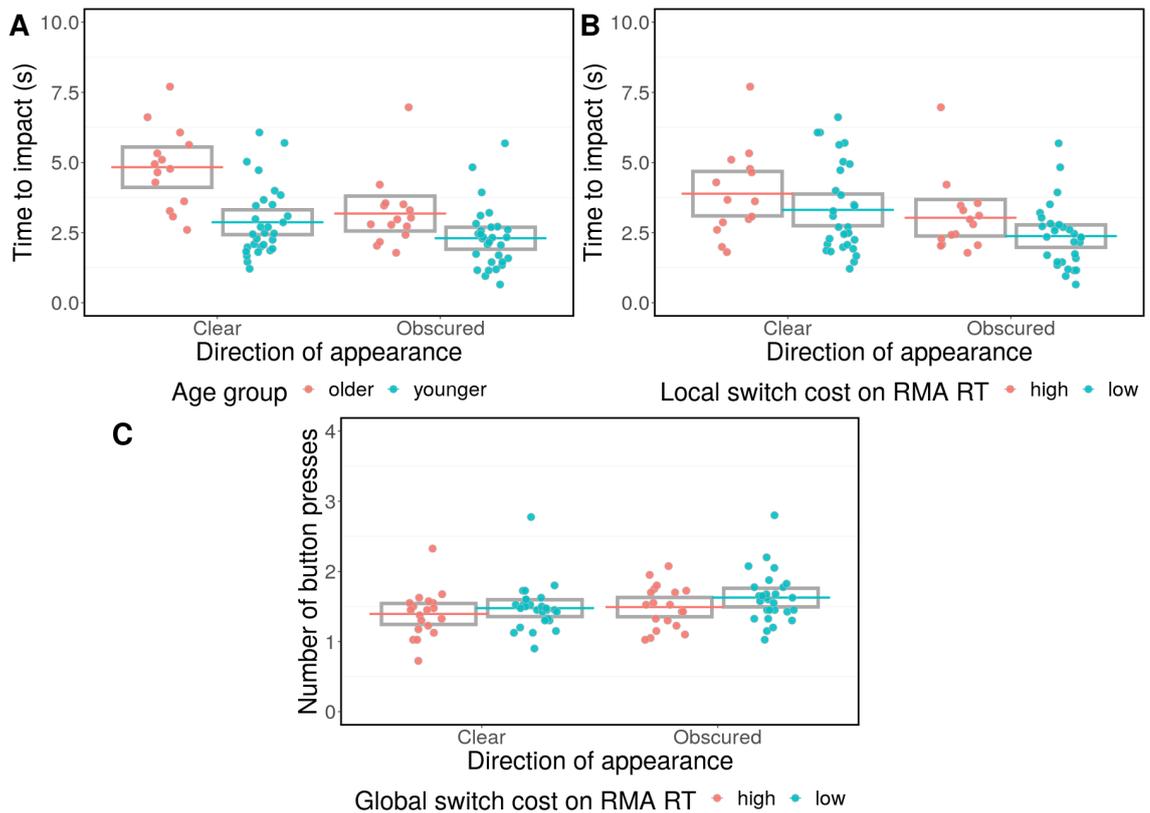


Figure 4.10: The effect of cars coming from an obscured view on the TTI (A) made by OAs and YAs, and participants with large and small local switch costs on the RMA task (B). The effect of cars coming from an obscured view on the number of crossing decisions made by participants with large and small global switch costs on the RMA task (C).

#### 4.8.4 Impact of traffic density on crossing behaviour

There was an interaction between executive functioning ability (spatial planning and attention switching) and traffic density on the number of crossing decisions participants made (BADS:  $\beta=-9.65e-03$ ,  $SE=4.81e-03$ ,  $t=-2.01$ ,  $p=0.045$ ; attention switching:  $\beta=0.03$ ,  $SE=0.01$ ,  $t=2.30$ ,  $p=0.022$ , Table C.7). All participants made fewer crossing decisions when traffic density was high compared to when traffic density was low. This decrease was greater for participants with high BADS zoo map scores, and participants with smaller global switch costs compared to participants with low BADS scores, and participants with larger global switch costs (Table C.7, C.12-C.16; Figures 4.11B, and A respectively).

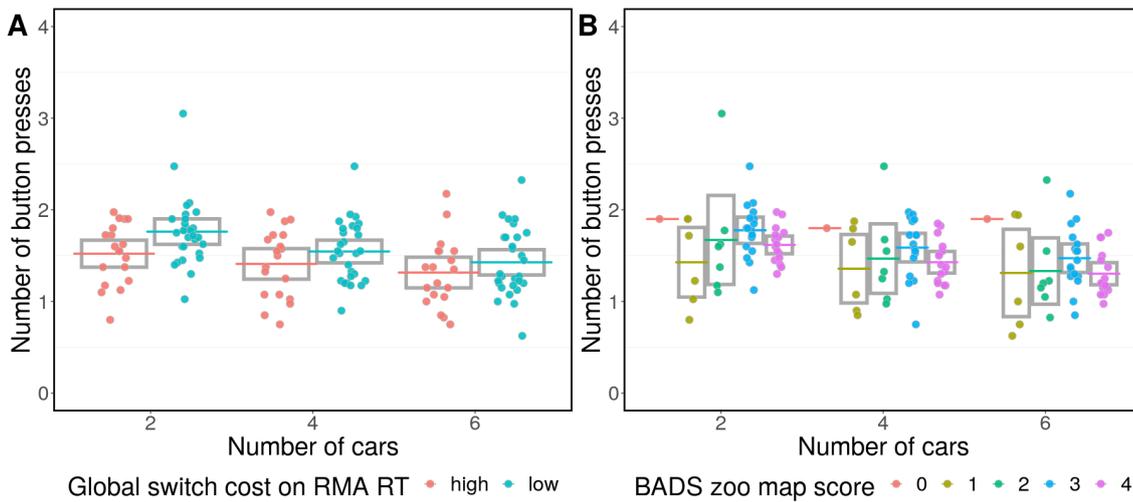


Figure 4.11: The effect of traffic density on the number of crossing decisions for participants with large and small global switch cost scores (A), high and low BADS zoo map scores (B).

#### 4.8.5 Impact of pedestrian distractors on crossing behaviour

I found no effects of pedestrian presence on the number, or duration of key presses participants made, or the TTI participants left (see Tables C.7, C.18, and C.34).

### 4.9 Discussion – Experiment 2

#### 4.9.1 Do OAs and participants with poorer executive functioning abilities show riskier crossing behaviour when task complexity is increased?

In line with the results from Experiment 1 the results from Experiment 2 reveal that all participants show riskier crossing behaviour when task complexity is increased, as participants reduced their TTI when task complexity increased. The impact of increased task complexity was again greater for OAs and participants with poorer executive functioning abilities than YAs and participants with better executive functioning abilities. The increase in risky crossing behaviour did not occur for all the ways in which task complexity was modulated. The increase in risky crossing behaviour occurred when cars travelled quickly, and when the viewpoint of the cars was obscured. The increase did not occur when cars travelled from both directions,

traffic density was high, and pedestrian distractors were present.

#### **4.9.2 Conditions that negatively impact on crossing behaviour**

As mentioned in Experiment 1 when cars travel faster or from an obscured direction the time participants have to determine a safe TTI is reduced due to the cars moving faster or the cars are closer to the participants when they become visible. As discussed in Experiment 1, reasons for the riskier behaviour come from participants having less time to react or to process the speed of the cars. Another reason for this behaviour may come from evidence showing that participants mainly base their time to contact judgements on distance rather than speed (Andrea, Fildes, & Triggs, 2000; Connelly et al., 1998; Hunt, Harper, & Lie, 2011; Simpson et al., 2003). Therefore, participants in this experiment may be releasing the button when the cars reach a certain point along the road, irrelevant of the speed of the vehicles. Releasing the button when cars get to this point along the road may give safe TTIs when cars are travelling slowly but not when they are travelling quickly. Had participants focused on the speed of the vehicles they would have realised that they needed to release the button earlier, which would have reduced their TTI. Training participants to use both speed and distance information may help participants adapt their safe crossing distance to different car speeds, and improve the safety of their crossing behaviour.

In the case where the viewpoint of the cars was obscured the distance participants decided was safe was forcibly reduced. The safest strategy in this situation would have been to not cross at all or release the button prior to the appearance of the car. In a real road crossing situation participants may not have crossed in a place where their view of the cars is obscured but in a laboratory setting they may feel they need to make a crossing decision, as they may feel that is what is expected of them. Future research investigating the differences between crossing decisions in a laboratory setting and a real road crossing would need to be conducted to determine if participants feel the need to cross more often in the laboratory.

Looking specifically at when cars travelled quickly, in Experiment 1 I found that

even though participants with poorer spatial planning abilities were more impacted than participants with better spatial planning abilities, they still had longer TTI than participants with better spatial planning abilities. In this experiment participants with poorer spatial planning abilities reduced their TTI to a point where it was similar to the amount of TTI left by participants with better spatial planning abilities. As discussed in Experiment 1 participants with poorer spatial planning abilities may have longer TTI than participants with better spatial planning abilities because they might be taking into account their slower ability to plan or execute their plans. In this experiment participants with poorer spatial planning abilities had the same TTI as participants with better spatial planning abilities. This suggests participants with poorer spatial planning are no longer able to compensate for their slower execution or planning, perhaps as a result of having to take into account both cars travelling from both directions and cars travelling quickly. Therefore, individuals with poorer spatial planning abilities may be more at risk when cars travel quickly than individuals with better spatial planning abilities as they are no longer able to take the extra time they need to cross safely.

When cars travelled quickly all participants reduced their TTI but OAs did not change their number of crossing decisions while YAs decreased their number of crossing decisions. Shorter TTI would increase the likelihood of an accident as it would leave participants less time to cross in a real road crossing. YAs might be mitigating this increased likelihood of an accident by making fewer crossing decisions, therefore reducing their likelihood of an accident by reducing their exposure (Keall, 1995). OAs are not mitigating the increased likelihood of an accident resulting from a reduced TTI by reducing their exposure as YAs do. Therefore, the likelihood of an accident may be higher for OAs than YAs when cars travel quickly.

When cars travelled from an obscured viewpoint I found that participants with poorer attention switching abilities were more impacted than participants with better attention switching abilities, as they reduced their TTI by more than participants with better attention switching abilities. As participants with poorer attention switching abilities were typically OAs, the larger reduction in TTI for participants

with poorer attention switching abilities may also result from the slower RTs among OAs than YAs.

### **4.9.3 Conditions that do not impact or impact positively on crossing behaviour**

When cars travelled from both directions, traffic density was high, or pedestrians were present, participants' crossing behaviour did not become more risky as participants did not decrease their TTI or increase their number of crossing decisions in these conditions. When traffic density was high and when cars travelled from both directions participants tended to behave more cautiously as they either reduced their number of crossing decisions or increased their TTI in these conditions.

When cars travelled from both directions, traffic density was high or pedestrians were present the task complexity is increased for the participants as there are more objects in the scene that participants have to keep track of. For example, when cars travel in both directions and both lanes participants need to initially look towards one side of the road, take in the position of the cars, make an estimate of their speed so they can predict when the cars would reach the participants position, and ignore pedestrian distractors. All this information has to be taken in and held in the memory while participants look to the other side of the road and make the same judgements about the cars coming from the left. Therefore, the working memory load for the participants is higher in these conditions than when cars come from one direction, no pedestrian distractors are present or traffic density is low. Despite the increased working memory load all participants were still able to maintain the same level of TTI, or had longer TTI compared to when the task complexity was not as high. This was even the case for OAs and participants with poorer executive functioning abilities that are known to have smaller working memory capacities than YAs and participants with better executive functioning abilities (Bopp & Verhaeghen, 2005; Carpenter, Just, & Shell, 1990; Owen, Downes, Sahakian, Polkey, & Robbins, 1990; Phillips et al., 2003; Schneider-Garces et al., 2010; Welsh, Cicerello, Cuneo, & Brennan, 1995). However, when cars appeared from both directions and

pedestrians were present there was only one to two additional objects that participants had to keep track of compared to when cars appeared from one direction or no pedestrians were present. Therefore, these conditions may not have increased the working memory load enough to exceed the working memory capacity of OAs and participants with poorer executive functioning.

When traffic density increased the number of cars increased from two to a maximum of six cars. This would be four additional items participants had to keep track of. However, as all the cars travelled together participants may have visually grouped the cars and so treated them as one object (Gillam, 1992; S. E. Palmer, 1992; Wertheimer, 1923). This would mean that the working memory load on the participants would not have increased with an increase in traffic density and the task would not have been more complex. Future research should be done to investigate the role of working memory capacity in realistic scenarios and what the working memory capacity limit is for OAs and participants with poorer executive functions in these scenarios.

Participants might be better at identifying that a road crossing situation is more dangerous when there are more objects in the scene for example when cars appear from both directions, than when cars travel quickly or from an obscured viewpoint. If participants identify situations such as high traffic, cars coming from both directions, or pedestrian being present as dangerous then they would behave more cautiously and increase their TTI or reduce their number of crossing decisions. By contrast, if participants are less able to identify that cars travelling quickly or from an obscure viewpoint are dangerous situations than conditions where there are more objects on the screen, they may not behave more cautiously. Future research should determine whether participants find particular scenarios easier to determine the level of danger present and how this affects participants' crossing behaviour.

The findings for cars travelling from both directions are in contrast to the findings in the literature that OAs and participants with reduced executive functions made riskier decisions when cars travel along both directions (Dommes et al., 2013; Geraghty et al., 2016). This may be due to the current experiment only having one

wave of cars appear on the trial with a consistent gap between them. Dommes et al. (2013) had two waves of cars at different speeds and varied the gaps between the first and second wave, while Geraghty et al. (2016) used a video recording of a natural scene with natural traffic flow. A natural traffic flow would be more challenging as participants would not be able to just wait until all cars have passed by before making a decision, they would need to cross between two vehicles. OAs may have more difficulties picking appropriate gaps between vehicles. This could be investigated by randomising the gap between the cars and the time points they appear on the trial or by performing the experiment at a real crossing but preventing participants from actually crossing the road to maintain participant safety.

Focusing on the pedestrian distractor condition, participants did not change their crossing behaviour in response to pedestrian distractors being present. These results match those in Chapter 3 where participants' crossing decisions were not impacted by pedestrian distractors. As I were unable to analyse eye tracking data it is unclear whether OAs gaze would have been drawn by pedestrians as in Chapter 3. The results for this experiment may have been similar to those in Chapter 3 in that OAs' gaze may have been captured by the pedestrians but OAs were still able to make safe crossing decisions or OAs may have chosen to gaze at the pedestrians once the cars have passed the OAs or prior to the appearance of the cars. Alternatively, OAs may not have had their gaze captured by pedestrians at all. If pedestrian distractors did not capture the overt attention of OAs then further research should be done to determine why pedestrians do not capture attention.

## 4.10 Conclusion

In summary, I find that although participants are able to make safe crossing decisions in simple situations, in more complex situations all participants have more difficulties. When cars travelled quickly or from an obscured viewpoint participants, in particular OAs and participants with poorer spatial planning abilities, showed riskier crossing behaviour. These findings can be used to determine whether training methods can be developed for not only OAs but also YAs to see whether

this would help them improve the safety of their crossing decisions when cars travel faster. Alternatively, infrastructure changes, such as speed limits, could be implemented in more locations around cities and especially by retirement homes and villages.

Once the eye tracking data is available I will also be able to investigate whether OAs and YAs or participants with different executive functioning abilities have different attentional crossing strategies and how this relates to crossing behaviour. Not only this, but whether participants change their strategies in situations such as when cars travel quickly and if these strategy changes lead to the riskier crossing behaviour. This would also allow us to develop training methods based on the optimum gaze strategy either overall or for specific situations.

# Chapter 5

## In pursuit of visual attention: SSVEP frequency-tagging moving targets

This chapter has been published as: de Lissa, P., Caldara, R., Nicholls, V., & Miellet, S. (2020). In pursuit of visual attention: SSVEP frequency-tagging moving targets. *PLOS ONE*, *15*(8), e0236967. My contributions included experiment design and analysis.

### 5.1 Introduction

In daily life we experience a large variety of situations in which we need to visually track multiple objects at the same time, for instance when crossing a busy street, monitoring the safety of children playing in playgrounds, locating a spouse in a bustling shopping centre, etc. In these situations we can make use of a division of visual attention as we monitor both moving and stationary objects across time, often rapidly switching between attending to targets through direct eye-movements or through our peripheral visual fields. The need to modulate our attention arises from inherent limitations in our capacity to attend to the broad array of stimuli our senses may provide to us at any one moment (Kahneman, 1973; Lavie, Hirst, De Fockert, & Viding, 2004). The Perceptual Load Theory advanced by Lavie and

others conceptualises attention as a limited pool of resources that we are able to devote to the processing of targets and distractors in various environments. The balance of our attention directed to spatial locations at any given moment is thus related to the perceptual load of the tasks being concurrently performed (Lavie & Tsai, 1994; Lavie, 1995, 2005, 2010). The way in which the brain modulates visual input through attention has additionally been conceptualised as a mechanism that decreases the salience of distractors by reducing the neural sensitivity to unattended stimuli so that attended stimuli experience less competition while they are processed (J. Moran & Desimone, 1985; Reynolds, Chelazzi, & Desimone, 1999; Sundberg, Mitchell, & Reynolds, 2009). When applied to contexts and tasks that require the visual analysis of complex scenes involving both moving and stationary objects, these theories suggest a modulation of attention that depends on the requirement of attention to be either divided or singularly focused (Lavie & Tsai, 1994; Lavie, 1995, 2005, 2010). Part of such a dynamic involves attention directed to what we are directly foveating (overt attention), as well as attention directed to areas outside our foveal fields in our parafoveal or peripheral visual fields in the form of covert attention (Posner, 1980). While overt visual attention can be indexed through the recording of eye-position during various tasks, covert shifts of attention to areas outside of foveal regions are by their nature often not accompanied by explicit behavioural measures and must be measured indirectly through analyses of reaction time in paradigms involving cueing to extra-foveal spatial locations compared to either an un-cued or an incorrectly cued location (Posner, Nissen, & Ogden, 1978; Posner, Snyder, & Davidson, 1980).

Aligning with the view of attention to be a limited pool of resources, some studies have suggested that when covert attention is directed to spatial areas in the periphery there is a decrease in attention directed towards foveated stimuli (Mishra, Zinni, Bavelier, & Hillyard, 2011; Zhou, Liang, Pan, Qian, & Zhang, 2017). However, competing evidence has suggested that both covert and overt visual attention may be deployed simultaneously in parallel in paradigms involving dual tasks without a notable decrease in performance (Heinen, Jin, & Watamaniuk, 2011; Ludwig et

al., 2014). The nature of the tasks in such paradigms is likely to play a critical role in how attention might be divided between overt and covert monitoring during analysis of objects in the visual environment. In the case of complex scenes this may involve a selection of what targets to monitor overtly with the eyes and which to monitor covertly through the shift of peripheral visual attention. What is yet to be clarified is how overt attention directed to a moving object is influenced by additional requirements to monitor other spatial locations with covert visual attention. This question is the basis of the current study.

While various behavioural tasks have been used to investigate the deployment of both overt and covert visual attention, it is possible to index the relative recruitment of these forms of attention by recording the neural responses in electroencephalographic (EEG) recordings to the flickering of stimuli presented in different spatial locations of the visual field. While the early occipital lobe responds to this flickering in a systematic way, the strength of this response is strongly modulated by whether the flickering objects/regions are being attended to or not, with larger responses to attended stimuli compared to unattended stimuli (Andersen & Müller, 2010; Y. J. Kim, Grabowecky, Paller, Muthu, & Suzuki, 2007; Morgan, Hansen, & Hillyard, 1996; Müller, Teder-Sälejärvi, & Hillyard, 1998; Störmer, Winther, Li, & Andersen, 2013; Toffanin, de Jong, Johnson, & Martens, 2009). Known as Steady-State Visual Evoked Potentials (SSVEP), this technique offers a complement to the measurement of behavioural responses, as it can capture the time-course of shifts of attention, contrasting with behavioural responses which, while influenced by attention, constitute the end-point of a chain of perceptual and decision-making processes. Indeed, an important benefit of the SSVEP approach is that it does not require a specific behavioural response, making it well-suited to investigate shifts of attention that take place without behavioural markers (Norcia, Appelbaum, Ales, Cottareau, & Rossion, 2015). Recent studies investigating attention allocation during smooth-pursuit paradigms have found clear neural responses to flickering stimuli in both peripheral regions (J. Chen, Valsecchi, & Gegenfurtner, 2017a) and to a general flickering background stimulus (J. Chen, Valsecchi, & Gegenfurtner, 2017b), with

the latter suggesting the neural responses during smooth-pursuit to be larger than when the eye-position is fixed. However, to our knowledge this paradigm has not yet been used to investigate overt visual attention during the tracking of moving objects or how it is affected by task-related shifts of covert attention.

Applied to the question of how visual attention is affected when extrafoveal areas are monitored while a moving target is simultaneously tracked by the eyes, the SSVEP technique offers a means of determining whether covert shifts of attention decrease the sensitivity to the moving foveal target as might be predicted if a limited pool of visual attention leads to a sacrifice of overt visual attention when deploying covert attention. In order to investigate this question while maintaining systematic control over low-level visual properties, the current study combined eye-position recordings with an SSVEP paradigm, measuring the neural responses to the flickering of targets as participants followed them with their eyes as they moved across a computer screen. The task consisted of overtly tracking a target as it moved across a computer screen and pressing a button when it entered a specific portion of the screen. However, in half of the trials the participants were instructed that a second target might also appear and follow the same trajectory as the first, whereupon they should perform the task on the second target instead. This manipulation created two conditions: An undivided condition where the task required overt attention only to one single moving target, and a divided condition where the expectation of a possible second target at a specific place and time provided the context where both overt and covert visual attention could be used in the task. The neural responses to the foveally-tracked target thus formed an index of overt attention, which would be significantly reduced in the case of shared and limited pool of attentional resources, when the participants covertly monitored for the appearance of a second target.

## 5.2 Methods

The Human Ethics Committee at the University of Fribourg approved the methods and procedure used in this study.

### 5.2.1 Participants

Twenty-two participants were tested in the current study. Four participant datasets were excluded due to insufficient trial numbers to form a meaningful condition average and one dataset was excluded due to strong contamination throughout the scalp originating from anterior/facial areas during the trials which introduced a distinct 10 Hz distortion and separate broadband distortion rising at 15 Hz and extending through to approximately 50 Hz, matching artefacts observed in previous studies of frontalis muscle activity (B. H. Friedman & Thayer, 1991; Goncharova, McFarland, Vaughan, & Wolpaw, 2003). Datasets were analysed from the remaining 17 participants (13 females, 17 right-handed), aged between 19 and 44 years (mean age = 26.5 years, SD = 7). All participants had normal or corrected-to-normal vision, and gave their informed consent before participating in the study. Participants were offered 50 CHF for their time or course participation credits.

### 5.2.2 Stimuli and procedure

Participants were instructed to follow a moving target as it moved across a computer screen and to press a keyboard button when the target entered a spherical “goal” portion of the screen. The targets consistently travelled along a diagonal path from the top-left part of the screen to bottom-right goal section (see Figure 5.1) at a speed of  $3.75^\circ/\text{s}$ . The target stimuli consisted of a black and white rectangle ( $1.05^\circ \times 2.10^\circ$  visual angle) checkerboard pattern alternating (reversing between black and white) at a consistent rate of 30 Hz against a white background. The 30 Hz flicker created the frequency tag used for the subsequent EEG analysis of visual attention.

Two experimental conditions were created by manipulating what participants expected to see in the trials. In one condition block, participants were instructed that only one target would travel across the screen in each trial, and that they should press the keyboard button when it reached the goal area. In the other condition block, participants were instructed that a second target might appear while the first target was still travelling across the screen (occurring in  $2/3$  of the trials in this condition). The second target (also flickering at the 30 Hz) appeared in the

same location as the first target at the onset of the trial so that participants had a specific and predictable target for a covert shift of attention. The second target appeared at either 2136 or 2270 ms into the trial, providing a consistent time range for participants to predict when to direct covert attention with a small range of variability. Participants were instructed that if a second target did appear they were to then track that second target with their eyes and press the button when the second target reached the goal area. This was to provide a task-related division of attention, while balancing all low-level visual properties between the conditions up until the appearance of a second target in the periphery. Participants were informed at the beginning of each condition block whether to expect either only one or more than one target, creating two experimental conditions; an undivided attention condition and a divided attention condition. The time-window leading up to the possible presentation of a second target thus formed the period of interest for our analysis, where shifts of attention relating to participants' condition-related expectations were predicted to occur. Analyses were performed on the entire trial time-range, with particular focus on the period of interest where the participants' eye-gaze was directly over the moving targets. Analyses on the time period preceding this period are provided with the caveat that the conditions during this time period were uncontrolled for low-level visual properties relating to where the stimuli appeared in the participants' visual field.

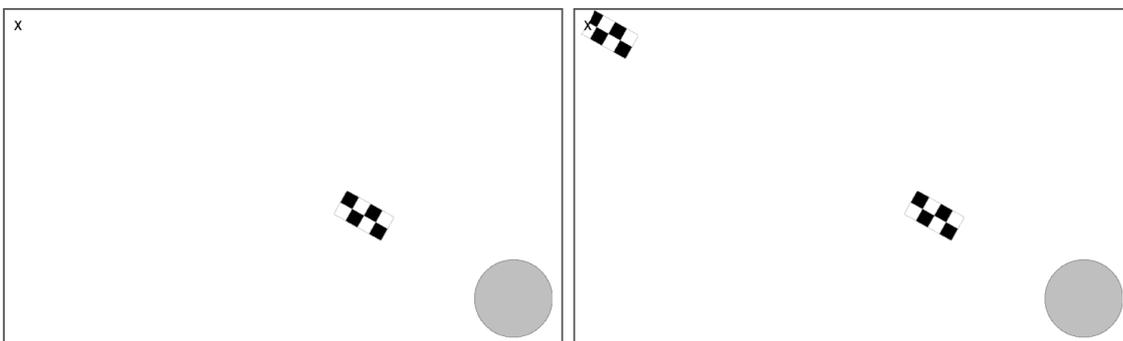


Figure 5.1: Alternating checkerboard targets emerged from the left side of the screen (denoted by “x”) and travelled across the screen to a circular region (left), whereupon participants pressed a button when they judged the target to be fully within the region. In half of the trials a second target had a 66% probability of appearing and travelling across the screen (right), where participants had to subsequently perform the button-press task on this second target instead.

There were 204 trials in total, with 102 in each of the divided and undivided attention conditions. The trials were divided into 4 alternating homogenous blocks, and the presentation order of these blocks was counter-balanced to avoid fatigue or order-effects by creating two block-orders presented to two participant groups (8 and 9 participants in the two counterbalanced groups). The experimental trials began with a fixation cross in the top left corner of the screen, corresponding to the region where the target would initially appear. When participants fixated on this cross area ( $1.3^\circ \times 1.3^\circ$ ), the cross would disappear and the target would begin to emerge from the top-left corner 266 ms later, becoming fully visible at 667 ms. The trials ended when the participant made their decisions relating to the targets completely entering the goal area (3170 ms into the trial in the undivided condition, 5003 or 5136 ms into the trial in the divided condition) by making a keypress. The experimental stimuli were presented on a 24 inch VIEWPixx/3D monitor (1920 x 1080 pixels, 120 Hz refresh rate) at a distance of 75 cm, and presented through Experiment Builder (v1.10.1630) software.

### **5.2.3 Eye movement recording and processing**

Eye-positions were recorded through a desktop-mounted Eyelink 1000 monocular (left) eye-tracker sampling at 1000 Hz. Calibrations of the eye-tracker (13-points, average position error  $< 0.5^\circ$ ) were performed at the beginning of the experimental blocks and after breaks in the trials. The onset of a trial was triggered by a fixation in a specified region in the top left part of the screen; if this was not fixated upon within 4 seconds after presentation then a re-calibration sequence was entered, ensuring effective calibration throughout each of the trials. The trials began with the flickering targets emerging near the upper-left portion of the screen 266 ms after trial onset. The early part of the trials was characterised by the target stimuli approaching and passing the participants' fixated gaze, and the subsequent orienting of their gaze to these moving targets through catch-up saccades. This orienting phase generally took approximately 500 ms before participants were able to align their smooth-pursuit eye movements with the movement of the targets. To allow for

this, a time-window of analysis for eye-gaze and EEG was created, beginning 1000 ms after the onset of the trial (734 ms after the onset the first target) and ending at 2000 ms (shortly before a second target might appear at either 2136 or 2270 ms).

The x and y gaze coordinates of the participants in the trials were exported and analysed to ensure that the flashing targets were directly foveated by the participants during a 1000 ms period immediately preceding the time at which the onset of a second target would occur. Trials were rejected if the participants were not directly foveating the targets for over 95% of this 1000 ms time period (allowing for transient loss of foveation and eye-blinks). A 1000 ms period of interest was chosen for two reasons: 1) it is preceding the likely appearance of the second target so we expect relevant processes associated with attentional shifts to occur in this period, and 2) this period starts after the catch-up saccade and when the smooth-pursuit is consistently initiated across trials. To ensure a reliable average, a critical threshold of 25 accepted trials was applied, which led to the rejection of 4 participants due to insufficient trials. The SSVEP technique has been found to yield a high signal to noise ratio, with analyses involving known oscillations (frequency tags) reliably measuring visually-entrained EEG responses from as little as 10 artefact-free trials (Miskovic & Keil, 2015), and from 15 trials in a face-detection paradigm using sweep SSVEP (Ales, Farzin, Rossion, & Norcia, 2012). Because the co-registration of EEG and eye-movements in the current study required rejection of EEG epochs where eye-gaze was outside of the stimulus regions, the potential for a high trial rejection rate was considered in the experimental planning, with 102 total trials per condition being presented to allow for a potentially large number of rejected trials. After this process an average of 39% of all trials were rejected. The average number of accepted trials in the divided and undivided attention conditions in the current study was much higher than this minimum threshold, with 65 and 60 accepted trials, respectively (see supporting Figure D.1). Bayes factor analysis was performed on the number of accepted trials between the two conditions, allowing for an interpretation of not only the likelihood of the data representing evidence in favour of a hypothesised difference between conditions, but of evidence in favour of a null-effect (Dienes, 2011). The

results suggested anecdotal evidence (for review of Bayes factor terminology see Wagenmakers et al., 2018) for the null hypothesis and no support for predicted differences between the conditions ( $BF_{10} = 0.825$ , 0.005% error). Bayes factor analysis was performed through JASP (0.11.1) software with default settings (JASP Team, 2019).

After the trial exclusion process, the remaining trials were analysed to determine whether there were systematic differences in eye-position between the divided and undivided conditions. Bayes factor analyses were performed at each time point between the appearance of the initial target (266 ms) and the end of the analysis period (2000 ms) using data that indexed the absolute distance (in degrees of visual angle) between the participants' eye-positions and the centre of the target at each time point. The results did not suggest evidence of a difference between the conditions throughout this period, instead they indicated a general tendency across the period to support the null hypothesis (divided absolute distance = undivided absolute distance), with an average  $BF_{10}$  of 0.309 and a maximum of 0.858 (see Figure 5.2e for  $BF_{10}$  values across the period of interest). The participants' accuracy at tracking the targets can be seen in Figures 5.2a, b, and c, which depict the distances at each time point that the participants' eyes were from the target centre in XY co-ordinates and in absolute Euclidean distance, measured in degrees of visual angle. A value of zero would therefore correspond to the centre of the target in either the X or Y plane. The high target-tracking accuracy in the current study is consistent with previous studies utilising targets of predictable speeds (De Brouwer, Yuksel, Blohm, Missal, & Lefèvre, 2002), and is in line with the results of a previous study showing that following the centre of a moving target facilitates the allocation of attention to peripheral locations when multiple objects are present (Fehd & Seiffert, 2010). The average distance from target centre for the undivided and divided attention conditions were  $-0.05^\circ$  and  $0.01^\circ$  respectively for the X positions, and  $0.03^\circ$  and  $0.02^\circ$  for Y positions. For reference, the length and width of the target stimuli were  $2.2^\circ$  and  $1.1^\circ$  respectively. The average precision (both group average and individual average) across the critical time-period is illustrated in Figure 5.2g,

which represents the average eye-positions on the target throughout the period of interest for the divided and undivided conditions.

We additionally analysed the frequency of saccades made during the trials, as saccades have been found to lead to a suppression of visual sensitivity for up to approximately 300 ms after their onset (J. Chen, Valsecchi, & Gegenfurtner, 2019). Saccade events of amplitudes ranging from  $1^\circ$  and  $38^\circ$  (largest plausible saccade, given screen size and distance) were detected through Dataviewer (version 1.11.900) using saccadic velocity and acceleration thresholds of  $30^\circ/\text{sec}$  and  $8000^\circ/\text{sec}^2$ , respectively. Saccade frequency was calculated by counting the number of saccades made by participants in each condition in bins of 50 ms width across the trial from 266 ms through to 2000 ms. The saccade count for each participant was then divided by the total number of trials in each condition to form an index of saccade probability, or proportion of the trials in which a saccade was made at each time bin. The early time range of the trials involved saccadic responses to the presentation of the moving targets, whereas the rest of the trial periods were characterised by a relatively low proportion of saccadic activity (see Figure 5.2d). Bayes factor analysis of participants' saccade probabilities revealed substantial evidence that there were more saccades in the undivided condition in the early time range covering 400 – 450 ms ( $\text{BF}_{10} = 4.156$ ), whereas at other time points no substantial evidence for a difference was found (see Figure 5.2f).

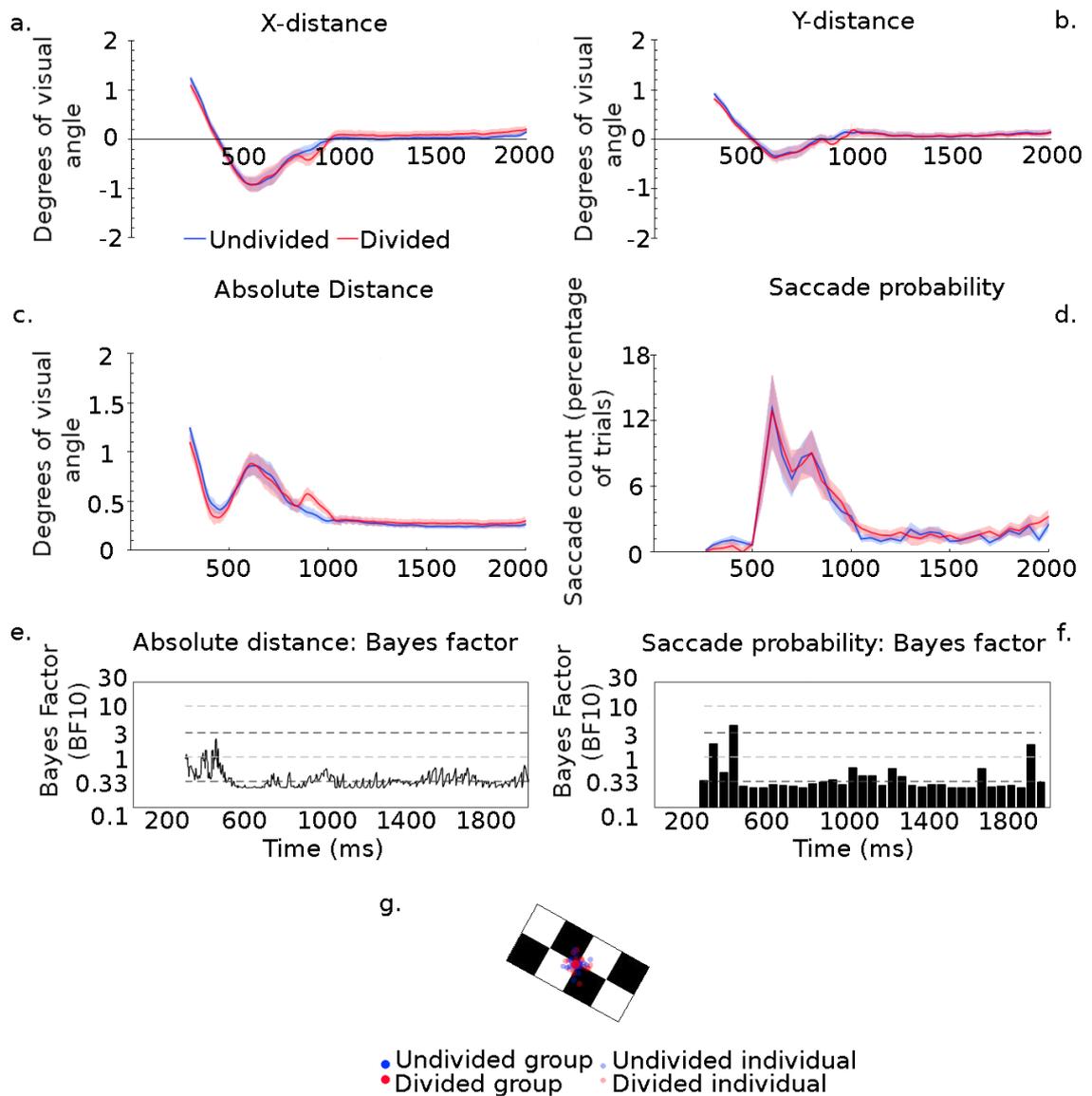


Figure 5.2: Eye-gaze distances from target centre for x (a), y (b), and absolute (c) measures, and the index of saccade probability throughout the trial until immediately before the possible appearance of a second target (standard error shaded). Bayes factor analyses did not find differences between conditions for absolute distance (e) or saccade probability (f) in the critical period of analysis. Fig 5.2g depicts the condition average eye-positions (solid large blue/red) relative to the targets throughout the 1000 ms interest period, as well as the individual participant averages (faded small blue/red).

To determine whether the incidence of eye blinks in the current study was modulated by condition, the mean number of blinks each participant exhibited in each critical period per condition was analysed through Bayes factor analysis. Blink events were detected using the default blink detection Dataviewer algorithm (version 1.11.900). On average the number of blinks per trial were very low, with 0.25 (SD=0.26) blinks per trial in the undivided condition and 0.22 (SD=0.23) in the di-

vided condition, as was the number of saccades (1.07, SD=0.59, and 0.99, SD=0.51, respectively). Bayes factor analysis indicated no significant differences in the incidence of eye blinks or saccades between the conditions (BF10) of 0.346 (0.003% error) and 0.595 (0.002% error) respectively, indicating anecdotal evidence in favour of the null hypothesis (no difference between conditions).

Participants' eye-movements were monitored during the testing session by the experimenters to ensure they understood and followed the task instructions. Participants initiated a saccade to the second target within 351 ms (SD=70 ms) of their appearance in relevant trials, suggesting an adherence to the task instructions. Following the pre-processing of eye-position data, only accepted trials were used in subsequent statistical analyses of task-related effects on EEG responses.

#### **5.2.4 EEG recording and processing**

Electrophysiological responses were recorded through a Biosemi Active-Two amplifier system, using 128 Ag/AgCl electrodes sampling at 1024 Hz. Additional electrodes were placed at the outer canthi and above of each eye, to register ocular movements and blinks. EEG data was processed offline through EEGLAB (14.1.0b) running in the MATLAB 2016b environment. After an initial bandpass filtering process (0.1-75 Hz, zero phase shift, linear finite impulse, Hamming window), epochs of 5000 ms duration were created, beginning at a -1000ms baseline period at the onset of the trial. To isolate and remove blink and eye-movement distortions, the 5000 ms epochs were subjected to Independent Component Analysis (ICA, using the 'runica' algorithm through EEGLAB, Delorme & Makeig, 2004). Independent components corresponding to frontal blink and saccade topographic distortions were isolated and removed from the data, as well as slow drift in EEG corresponding to smooth pursuit activity (see supporting Figure D.2). However, in a number of datasets this slow drift was not able to be isolated through ICA, even though a clear drift could be observed in the raw data. This was not problematic in the current experimental design, however, as the slow drift was not related to frequencies overlapping the 30 Hz frequency tag utilised in the study (see supporting Figure D.2a and b for ex-

amples of the frequency responses of independent components associated with blink and smooth pursuit distortions).

The EEG was subsequently re-referenced to a common-average reference, and epochs noted for rejection in the eye-gaze analysis were removed from statistical analysis, leaving only epochs where the participants were directly foveating the targets more than 95% of the critical 1000 ms period. Frequency power values were measured relative to a 1000 ms pre-stimulus onset baseline to quantify event-related spectral perturbation (ERSP) data in a normalized signal-to-noise ratio (SNR), and are hereafter presented in dB units (relative to pre-stimulus baseline). The frequency tag from a directly foveated flickering stimulus was predicted to lead to a corresponding neural frequency in the central-occipital region (Vanegas, Blangero, & Kelly, 2015), approximately between central Oz and Iz electrodes in a 10-20 system. This was confirmed with a fast-fourier transform of the full 1000 ms critical period, where a 30 Hz signal was observed in the central occipital region relative to the 1000 ms baseline period (see Figure 5.3a for a topographical representation of 30 Hz power). The frequency response spectrum at the posterior occipital cluster indicated a discrete spike in the 30 Hz frequency band (Figure 5.3b). This was complemented with a time-frequency decomposition using Morlet wavelet transformations within the range of 3-70 Hz (3 0.5 wavelet cycles; yielding higher resolution as frequency increased and a wavelet at exactly 30 Hz) to give insight into the timing of the 30 Hz signal from the beginning of the trial to the period immediately preceding the possible onset of a second target (2000 ms window), collapsing across the two conditions. The 30 Hz signal was observed in both the ERSP and inter-trial coherence (ITC) topographies to arise at approximately 750 ms in the central occipital region and continuing through to the end of the 2000 ms window.

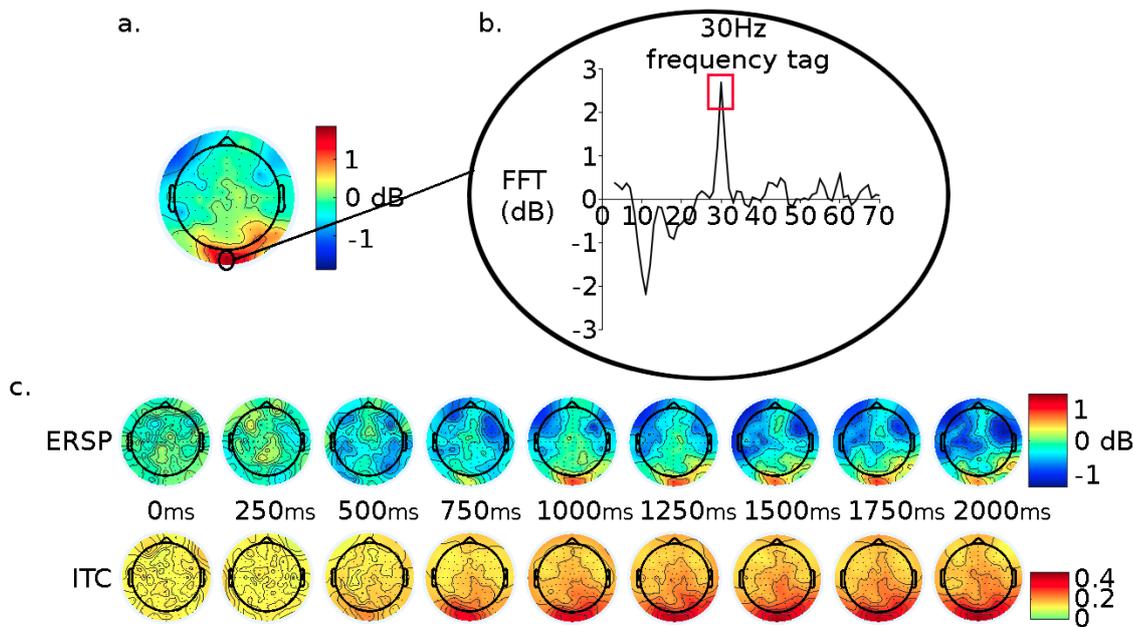


Figure 5.3: Scalp topography revealed a strong 30 Hz signal in the central-occipital region during the 1000 ms critical period (a), with a fast-fourier transform in this area indicating a distinct 30 Hz spike corresponding to the frequency-tag (b). Event-related spectral perturbation (c) and inter-trial coherence transforms found reliable 30 Hz signatures in the central-occipital regions arising at approximately 750 ms into the trial and continuing through the target-tracking period.

Following the confirmation of the 30 Hz frequency tag in the EEG recordings, statistical tests were conducted to compare the effect of divided visual attention on the power of the mean oscillation in the midline posterior occipital region corresponding to the Oz and Iz electrodes for all participants, representing the two electrodes with the largest 30 Hz signals (Figure 5.3a). Event-related spectral perturbations (ERSP) from the Morlet wavelet transformations from this region were computed for the divided and undivided attention conditions, producing ERSP averages of each condition for each participant. Differences between the divided and undivided ERSP data at each time point were compared with both Bayes factor analyses. The Bayes factor analysis gave an index of whether the 30 Hz ERSP power data provided support for hypothesised differences between the conditions across the time range, or whether a null-effect was more likely.

## 5.3 Results

Bayes factor analyses of the difference in 30 Hz power between the divided and undivided conditions (Figure 5.4 a & b) in the 1000 ms period of interest showed substantial evidence for hypothesised differences early in the time window ( $BF_{10} > 3$ ) from 1289 through to 1367 ms, and strong evidence ( $BF_{10} > 10$ ) from 1317 to 1331 ms (see Figure 5.4c). The source of these differences was observed to be due to greater 30 Hz power in the undivided attention condition compared to the divided attention condition. This difference and Bayes factor comparison can be observed in Figures 5.4c and d. Of note are results of the Bayes factor analyses for the other time points in the period of interest, where the  $BF_{10}$  values suggest substantial support for the null hypothesis, or no differences between the divided and undivided conditions ( $BF_{10} < 0.33$ ).

Analysis of the early trial period where the participants' eye-gaze was not controlled revealed an early period of substantial evidence ( $BF_{10} > 3$ ) for greater 30 Hz power in the undivided condition between 200–287 ms, overlapping the period in which the initial target appeared in the upper-left portion of the monitor.

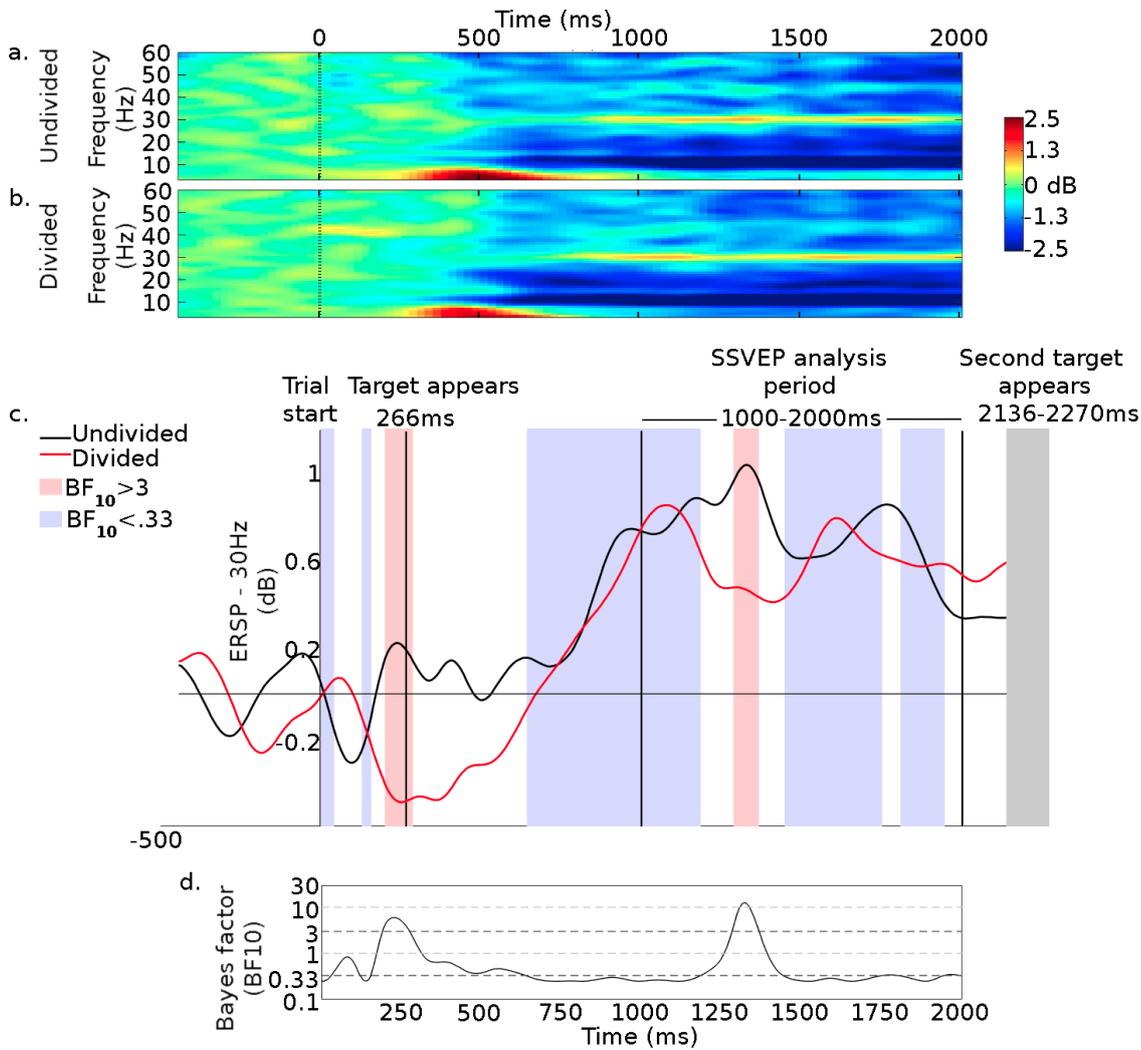


Figure 5.4: 30 Hz power (ERSP) across the trial period indicated sustained attention in both the undivided condition and divided attention conditions (a and b), with apparent decreases in neural response at discrete periods in the divided attention condition (c). The results of Bayes factor analyses suggested early discrete periods of difference between the conditions corresponding to the onset of the initial target and early in the critical analysis period (d). Grey lines denote the timing of events in the trials, and coloured shading denotes periods of Bayes factor evidence in favour of a condition effect (red) and of a null effect (blue).

## 5.4 Discussion

The current study sought to measure overt visual attention in a smooth-pursuit paradigm, and to determine whether allocation of covert attention to peripheral regions modulated measures of overt attention to a moving target. The SSVEP power corresponding to the 30 Hz frequency tag of the moving stimuli was found to decrease when the task required participants to attend covertly to where an additional target might appear in the periphery while concurrently tracking a moving

target. This period of difference, however, was both very short, and relatively early in the trial period. The lower SSVEP power in the divided condition aligns with the view of covert and overt visual attention as expressions of a pool of attentional resources, where an increase in covert attention can lead to a concomitant reduction in overt attention (Lavie et al., 2004; Kahneman, 1973), similar in nature to the reduction in SSVEP power to foveated static stimuli observed when covert visual attention is recruited (Mishra et al., 2011). The finding suggests that attention can be deployed covertly while tracking a moving target, which is also in line with the behavioural results of Seya and Mori (2012), who used saccadic response times to index covert attentional shifts to peripheral spatial regions. Similarly, they support the behavioural findings of Ludwig et al. (2014) suggesting that both covert and overt attention can operate in parallel. A notable difference between our methodology and that of Ludwig et al. (2014), however, is that we utilised a passive measure of overt visual attention through SSVEP rather than a behavioural index. Thus, our approach allowed us to investigate the fine-grained temporal modulations of overt attention resulting from allocation of covert attention, rather than the end-product. However, there are significant limitations to the inferences we can draw from the observed patterns in the current study. Although the difference in 30 Hz power was in line with the direction predicted from preceding studies, we had expected that such an effect would be observed with greater likelihood in the time leading up to the possible appearance of a second target as the utility of covertly monitoring for a second target increased. Not only did we not find evidence for this effect in the later part of the trial, the Bayes factor analyses suggested that there was substantial evidence that the conditions were indeed comparable. It would therefore be more precise to suggest that we did not observe evidence of a covert shift of attention impacting overt attention in the majority of the analysis period. The question then arises as to why an earlier period of difference was observed rather than a later one. An answer may lie in nature of the task itself, and of how visual targeting for covert monitoring or saccadic planning is achieved during dynamic smooth pursuit. The current study utilized expectation of the likely appearance of a

second target in the trials to create a task-related division of visual attention between a moving target and a defined area in the participants' left peripheral field. While this allowed the participants to know where to allocate covert attention in these trials, the timing of the appearance of second targets was also somewhat predictable. While it might have been a logical prediction that the effects of divided attention in these trials would be more likely to be observed as time advanced towards this critical moment, our data did not show this. Rather, differences in the neural response to the overtly tracked targets were reliably observed approximately 800 ms before the time a second target would have appeared. It is possible that within any one trial there are multiple discrete shifts of attention away from the moving targets, but that the timing or duration of such shifts are not systematic within the trials and thus do not reveal a statistically clear pattern when averaging across them. Another explanation for this pattern is that sustained covert shifts of attention are not required in order to quickly respond to the appearance of additional targets. Such an interpretation invites speculation as to why there was a transient period of reliable difference in SSVEP power early in the trial. Such an early, discrete period of reduced overt attention may reflect a process of the encoding of spatial locations for future monitoring through covert attention, where overt attention is impacted to a lesser degree after this encoding process has occurred. An early shift of covert attention to the spatial location where an additional target may appear might then be analogous to pre-saccadic shifts of attention noted to occur immediately prior to the onset of a saccade (White, Rolfs, & Carrasco, 2013). The reduction in SSVEP power during this early period could then be considered to be due to processes involving the future execution of eye-movements, rather than an ongoing sampling of covert visual areas in order to react quickly to a second target appearing. If the predictability of the time or location of potential distractor stimuli modulates the time or the strength of changes in overt visual attention during object tracking, then future studies might specifically manipulate these dimensions to determine how they contribute to such effects, and whether they interact with the task requirements. While our SSVEP results indicate that there was a reduction in overt attention to

the moving targets when the task required a covert shift of attention to a peripheral location, this, however, does not necessarily mean that a performance decrease would also be observed had an additional behavioural task been employed. This is in line with the perceptual load theory, which suggests that the division of visual attention across covert and overt areas is moderated by the processing load required by the tasks at hand. Accordingly, it is likely that modulating the salience of the moving target may also modulate the degree to which covert shifts of attention to peripheral locations affect the processing of the moving target, as smooth pursuit and saccadic programming have been found to share/compete attentional resources (Jin, Reeves, Watamaniuk, & Heinen, 2013). In contexts such as parents tracking moving children in a playground, or security forces monitoring moving threats, one dimension of the task involves accurately following targets with the eyes while an additional task might involve a specific visual analysis of the target itself. In these contexts, the level of overt attention may be higher than when there was no secondary task requiring visual analysis, making it more difficult (or less likely) for covert shifts to occur. It is also likely that additional visual analysis of the moving stimuli would require greater overt attention and thus may limit the amount of covert attention available for monitoring other spatial areas, as suggested by the finding that foveal distractors are harder to ignore than peripheral distractors (Beck & Lavie, 2005). The nature of any such task will likely then influence the relative strength of both central overt and peripheral covert visual attention, as competition between features for visual analysis and their distractors in central vision has been found to lead to an enhancement of neural sensitivity to peripheral regions (Painter, Dux, Travis, & Mattingley, 2014).

Apart from the window of ERSP difference observed in the SSVEP analysis period that was controlled for participants' eye-gaze, a very early period of difference was observed that corresponded with the onset of the initial targets' appearance in each trial (accounting for limitations in temporal resolution of ERSP values inherent in Morlet wavelet transformation). Interpreting this early difference is complicated by the nature in which the targets appeared, as they emerged incrementally over a

period of approximately 500 ms before being fully visible. Small differences in where participants were fixating in this early period may have projected the targets into different parts of their visual field, as only a small fraction of the images were visible at different times. Calculating the absolute difference of eye-gaze from the center of the targets is also problematic, as the centers of the targets were not yet visible until 250 ms after the edge of the targets emerged. Although our interpretations of this early effect is limited by these considerations, we do not rule-out the possibility that overt attention may be modulated by task, even in this early time period.

In consideration of how low-level factors might modulate both overt and covert visual attention during smooth-pursuit, other task-related dimensions may also significantly modulate the strength of overt attention such as the speed of the moving target, and the spatial locations of where covert shifts of attention are directed. Saccade latencies to stimuli presented during smooth-pursuit have been found to increase as target speed increases (Bieg, Chuang, Bühlhoff, & Bresciani, 2015; Seya & Mori, 2012). An SSVEP index of covert attention throughout the overt tracking of a moving target would allow for further clarification of how covert shifts of attention are influenced by target speed, and whether the effects pertain to the strength of covert shifts, the timing of such shifts, or both. Target-speed related modulation of covert peripheral attention is of particular concern in the domain of road-crossing safety, where increased vehicle speed may disproportionately affect individuals who tend to overtly track moving vehicles rather than covertly monitoring them through peripheral vision, as is the case with young children (Biassoni, Bina, Confalonieri, & Ciceri, 2018; Nicholls et al., 2019).

From a methodological perspective, the current study supports the use of the co-registration of eye-position recordings with SSVEP paradigms as a means investigating the dynamics of visual processing and attention while people perform tasks involving the tracking of moving objects. The development of this approach has recently shed light on the spread of attention during smooth-pursuit, with (J. Chen et al., 2017a) providing electrophysiological evidence that visual attention is directed slightly ahead of targets as they move across the visual field, supporting

behavioural results suggesting the same pattern (Khan, Lefèvre, Heinen, & Blohm, 2010; Van Donkelaar & Drew, 2002). A natural convergence of the current study with that of J. Chen et al. (2017a) would be to investigate the relationship between overt visual attention directed at a moving target and the default spread of attention while visual analysis of the target is taking place. The paradigm is also readily adaptable to investigate both overt and covert attention where multiple moving objects require selection or detection through either overt or covert visual attention (Lappin, Morse, & Seiffert, 2016). The inclusion of a passive neural index of visual attention in such paradigms provides another layer of measurement when determining the timing or intensity or attentional shifts in complex visual environments.

Methodologically speaking, there are a number of technical dimensions that must be addressed in order to obtain reliable SSVEP patterns that can be readily interpreted. The major concern is the control of low-level visual properties. It is imperative that participants' eye-positions are monitored throughout the SSVEP trials, as the relative position of such stimuli in the visual field significantly modulates both the intensity and topography of the recorded signals (Grgič, Calore, & de'Sperati, 2016; Müller et al., 1998; Punsawad & Wongsawat, 2017). This process will likely lead to the rejection of a certain number of trials involving inappropriate gaze-positions, and so the experimental planning needs to account for this reduction either by including a high number of trials, or an online index of gaze-accuracy which can repeat trials when necessary to compensate for rejected trials. Providing sufficiently large frequency-tagged stimuli may also in part address this concern, as large stimuli require less accurate gaze in order for them to be directly foveated. In addition, it is likely that some tasks and conditions might involve differences in target-tracking accuracy, where specific conditions or contexts are more likely to elicit saccades that are difficult to inhibit (or in populations where such inhibition might be impaired). An analysis of trial rejection may therefore provide an index of this, as well as more in-depth analysis of gaze-behaviour in the trials as a means of relating such behavior with visual attention during periods of target pursuit (Renton, Painter, & Mattingley, 2019). However, experimental conditions with significantly

different numbers of accepted trials might further complicate the interpretation of the comparison of SSVEP responses in these conditions as the signal-to-noise ratios in the EEG averages is strongly affected by this factor.

In summary, the application of SSVEPs to index covert visual attention while tracking a moving target provides a useful tool for understanding the effects of task-related covert attentional shifts in terms of both strength and timing. The results of the current study suggested a period of reduced visual attention to a moving target when the task involved the appearance of a possible second target. However, the transience and the early timing of the effect did not suggest a sustained difference in visual attention as the appearance of a second target grew more likely, suggesting a more complex dynamic between overt visual attention and covert shifts of attention during smooth pursuit. Accordingly, the co-registration of EEG and eye-position while using the SSVEP technique would thus be well-suited to exploring such dynamics in future studies.

# Chapter 6

## General Discussion

### 6.1 Overview of research findings

The overarching aim of the research presented in this thesis was to assess the link between attentional control and road crossing behaviour. Specifically, I investigated how the deficits in top-down attentional control in children and older adults influence their ability to make safe crossing decisions.

In the last 20 years top-down processes have become of increasing interest as the study of visual processing has sought to involve more natural conditions and realistic stimuli. These top-down processes have been shown to change as we go from childhood to adulthood as well as when we go from younger to older adults. Children have a lack of top-down attentional control (Colombo, 2001; Munoz & Everling, 2004; Paus, 1989) which does not reach adult levels before 10-12 years old (Fukushima et al., 2000; Irving, Tajik-Parvinchi, Lillakas, González, & Steinbach, 2009; Leclercq & Siéoff, 2013). Older adults show a deficit in attentional control compared to younger adults (Juncos-Rabadán et al., 2008; Pick & Proctor, 1999; Vu & Proctor, 2008). These types of developmental changes and age-related declines in our visual attentional control can lead to problems in day to day situations. One day to day activity in which attentional control has been linked to performance is that of road crossing (Schwebel et al., 2012). Although suggested this link has not been thoroughly investigated. In this thesis I aimed to see whether these deficits in top-down attentional control by children and older adults may explain why these

age groups are involved in the majority of traffic accidents (BITRE, 2015; ERSO, 2018; World Health Organization, 2015). To achieve these aims I carried out four experiments. My findings from these experiments show that children below the age of 10 are less able to inhibit attentional capture by distractors, which increases the risk of unsafe crossing decisions. In similar, simple situations, older adults also show an attentional bias towards distractors, but they maintain the ability to make safe crossing decisions. Systematic manipulations of the complexity of the road crossing scene revealed that older adults make riskier crossing decisions in specific situations such as when cars travel quickly. This research furthers our understanding of attentional control changes through the lifespan as well as providing insights for pedestrian safety. As such, it provides avenues for the development of training and safety guidelines for pedestrians. In the remainder of this discussion I provide a summary of my experiments and their findings, I then discuss the findings in more detail, and the future directions for my research.

In Chapter 2 I presented children aged between 5 and 15 y/o with a filmed road crossing scene and participants had to indicate, with a key press, when they thought it was safe to cross. I recorded their visual exploration while they did this. Younger children made more crossing decisions than older children, and young adults. The increased number of crossing decisions were linked to younger children being less able to inhibit their attention being drawn by pedestrian distractors. Moreover, when perceptual load was high (high traffic density) younger children were unable to disengage their attention from the vehicles. Together these results link children's reduced ability to control their attention from a top-down perspective and their ability to make safe road crossing decisions, and isolate the critical age at which children start to perform at adult levels.

In Chapter 3 I performed the same experiment with older adults that did not show executive functioning decline. Older participants showed a general cognitive slowing and had their visual attention captured by distractors, but they were able to make safe crossing decisions. This was achieved by adopting a conservative strategy of crossing less often and choosing larger crossing gaps (larger time to impact, TTI).

Lobjois and Cavallo (2007) suggested that older adults are able to make similar crossing decisions by accepting larger traffic gaps than younger adults to compensate for their slower walking speed. It has also been suggested that older adults can recruit additional neural resources in the frontal lobes in order to perform at the same level as younger adults. However, on tasks that are more complex the resource ceiling is reached and older adults are no longer able to perform at the same level as younger adults (Reuter-Lorenz & Cappell, 2008). Similarly, it is possible that the older adults in this study took into account their cognitive slowing when making crossing decisions. Considering that the second study used an environment with a single lane of traffic, I thought it would be critical that future studies determine if compensatory strategies are still effective in more complex environments that are more taxing for executive functioning.

In Chapter 4, using virtual reality, I systematically manipulated the number of driving directions, lanes car speed, traffic density, and the presence of distractors in order to formally explore how the situation complexity interacts with executive functioning to impact visual exploration, attentional control and decision making for pedestrians. I found that in specific situations such as when cars travelled quickly or from an obscured viewpoint all participants reduced their TTI which was amplified in older adults and older adults with declining executive functioning abilities. These findings can be used to see whether training methods can be developed for not only older but also younger adults to see whether this would help them in situations where cars move faster. Alternatively, infrastructure changes, such as speed limits, could be implemented in more locations around cities and especially by retirement homes and villages.

In Chapters 2 and 3, participants looked predominantly at the point where cars appeared on the road and did not overtly follow the cars down the road. This finding suggested a dissociation between overt and covert attention in the context of road-crossing. In order to explore this dissociation and its potential deficit in children and older people, in Chapter 5 I developed a technique used in conjunction with eye-tracking and steady state visually evoked potentials (SSVEP). In this paradigm,

participants overtly tracked a moving object and covertly monitored the appearance of a new object at the appearing point. I found a drop in the SSVEP power signal prior to the appearance of the second moving object while the participants' eyes were still overtly tracking the first object. This result suggests that during smooth pursuit there is a decrease in attentional resources allocated to the foveated object when there is a shift of covert attention towards a second object. In future studies, I aim to use this paradigm to explore more precisely the dynamics of overt and covert attention in a more realistic scenario and with children and older participants.

## **6.2 Discussion of findings**

### **6.2.1 Discussion on individual chapter findings**

Overall the research in this thesis highlights the importance of visual attentional control processes in doing every day activities such as crossing the road. My findings from Chapter 2 that overt visual attention of children below the age of 10 is captured by task irrelevant distractors is in line with findings from psychophysics studies (K. Hwang et al., 2016; Legrand, Mazars, Lemoine, Nougier, & Olivier, 2016; Paus, 1989; Paus, Babenko, & Radil, 1990; Ross, Radant, Hommer, & Young, 1994). Psychophysics studies typically use 'low-level' stimuli such as a red 'x' or a white cross for participants to make a saccade towards. It was unclear whether these findings would apply to more naturalistic stimuli. As explained above, more naturalistic situations and stimuli involve top-down processes more strongly. Thus, it is possible that the complexity and realism of the task influences the critical age at which children show stronger oculomotor capture and decreased inhibition of responses to task irrelevant distractors compared to adults.

Using static natural images, Aık et al. (2010) found that children under the age of 10 use oculomotor strategies particularly influenced by bottom-up processes. However, it was still unclear whether this would be the case with natural moving stimuli. More recently, Kuhn and Teszka (2017) explored differences in attentional control between adults and children within a more natural context, a magic trick.

They found that children below the age of 10 were more distracted than adults and this influenced how they experienced the world around them. My experiment also used natural dynamic stimuli, videos of a road, and I also found that task-irrelevant distractors captured the attention of children below the age of 10, while this was not the case for older children and adults. This was linked with younger children making riskier crossing decisions, suggesting that children's ability to inhibit the capture of their overt attention by distractors can impact how they interact with the world around them. My study and the studies by Aık et al. (2010) and Kuhn and Teszka (2017) suggest that the findings originally shown when using low-level stimuli apply to more natural situations. Not only this, but my study is the first to show this critical age of 10 years old applies in situations that children come across everyday, such as road crossing. Even so, there is a confound in these studies as it is unclear what type of distractor (simplistic image features e.g. image colours or more natural e.g. human pedestrians) has more of an influence on the capture of children's visual attention. This confound could be solved in an experiment using low-level visual distractors on half of the trials and social distractors on the other half of the trials and assessing whether low-level distractors have the same impact as social distractors. The influence of each type of distractor could be assessed by using feature maps.

In Chapter 2 I found a critical age of around 10 y/o above which children's gaze behaviour and crossing decisions are more similar to that of younger adults. This study used a relatively simplistic scenario in that participants only had to make crossing decisions based on cars travelling along one direction. This critical age may be higher in a more challenging situation such as when cars are travelling along both directions or when cars are travelling quickly. When cars travel along both sides of the road participants have to track more cars, and they have to hold the location of more cars in their memory when turning their heads. Both working memory capacity and the number of objects that can be tracked at the same time are still maturing beyond 10 y/o, into late adolescence (Dye & Bavelier, 2010; Hooper, Luciana, Conklin, & Yarger, 2004; Luciana, Conklin, Hooper, & Yarger, 2005; Luna

& Sweeney, 2004). Therefore, in more complex situations, such as when cars travel from both directions older children might also have difficulties resulting in a later critical age at which children make adult-like crossing decisions. Further research would be needed to verify this. The virtual environment I developed in Chapter 4, with the wide field of view so that participants are able to see both sides of the road would be an ideal set up to investigate this.

In Chapter 2 I also found that older children and younger adults gaze mainly at the appearing point. Assuming that younger adults adopt a near optimal strategy, the appearing point is an efficient fixation location for assessing as early as possible the vehicle's speed and TTI. Moreover, this gaze location allows the pedestrians to monitor for new vehicles entering the lane, thus to detect gaps, or end of gaps, very early. As the vehicles approach closer to the pedestrians they could easily be tracked using peripheral vision as their retinal projection gets larger. Adults and children from 11 y/o seem to be able to use this visual strategy regardless of the traffic density. In contrast, in higher traffic density trials (more than three vehicles), 5-10y/os follow the vehicles rather than maintaining their gaze at the appearing point. One suggestion for this would be that children are less able than adults at focusing on one area overtly and covertly tracking objects in their peripheral vision, forcing children to shift their overt attention between the appearing point and the cars travelling down the road. To assess which strategy is used by adults and children I plan to modify the eye tracking and SSVEP paradigm I developed to more closely match the road crossing scenario in the videos. More details on this are presented in the future directions section below.

Similar to the findings with young children, in Chapter 3 I found that older adults also showed overt attentional capture by pedestrian distractors. One explanation might be due to the relatively simple task in Chapter 3, in that they only needed to make crossing decisions based on traffic coming from one direction. As older adults are experienced road users they may have made a crossing decision quickly and spent the rest of the trial time looking at pedestrians. Another explanation may be that older adults had an inability to inhibit overt attentional capture by

pedestrian distractors. This is consistent with previous research using simplistic stimuli such as flashing dots (Crawford et al., 2013; Milham et al., 2002; Olincy et al., 1997). Previous studies have shown that older adults' reduced ability to control this inhibition of attention is associated with a selective inability to effectively use top-down suppression of neural activity associated with distracting information (Gazzaley & D'Esposito, 2007), in connection with a decreased involvement of the dorsolateral prefrontal (DLPFC) and parietal regions of the brain (Milham et al., 2002). It has been suggested that despite these declines in neural activity in the DLPFC older adults are able to recruit additional neural circuits. For example older adults have been shown to recruit the rostralateral (RLPFC) and anterior areas, that are typically involved in holding information in working memory and abstract thinking, to perform at the same level as younger adults on attentional and executive control tasks (Hsieh & Fang, 2012; Leshikar, Gutchess, Hebrank, Sutton, & Park, 2010; Luszcz, 2011; Rajah, Languay, & Valiquette, 2010; Reuter-Lorenz & Cappell, 2008). This additional recruitment of neural resources may be the reason older adults show similar crossing behaviour to younger adults in Chapter 3. This compensation hypothesis suggests that the reason the additional brain regions are recruited is because the same task results in a higher load for older adults than younger adults and therefore they need to recruit additional neural resources to bolster performance (Anderson, Campbell, Amer, Grady, & Hasher, 2014; Reuter-Lorenz & Cappell, 2008). This may be effective up until no further neural resources or brain regions can be recruited, as the resource ceiling has been reached (Reuter-Lorenz & Cappell, 2008). The compensatory hypothesis as the reason for older adults recruiting additional neural resources when performing the same tasks as younger adults is still debated in the literature (Morcom & Henson, 2018).

In the previous paragraph I discuss that the compensatory hypothesis may be a reason that older adults' overt attention is captured by pedestrian distractors but older adults are still able to make safe crossing decisions. The frontal regions such as the DLPFC are still maturing during childhood which has been linked to children's inability to inhibit their attention being captured by distractors (Colombo, 2001;

K. Hwang et al., 2010; Munoz & Everling, 2004; Paus, 1989). Another similarity with older adults is that children have also been shown to recruit additional neural regions such as the RLPFC when performing abstract thinking tasks (Dumontheil, Burgess, & Blakemore, 2008; Dumontheil, 2014; Wendelken, O'Hare, Whitaker, Ferrer, & Bunge, 2011). However, as far as I am aware this has not been discussed in the context of a compensatory hypothesis. The additional recruitment of frontal brain areas in children has not been associated with the same benefits on task performance as it has in older adults. This would contrast with the compensation hypothesis, as the compensation hypothesis suggests that the recruitment of additional resources allowed older adults to perform at the same level as younger adults. Further research should be conducted to determine why children recruit these additional frontal areas, and in what contexts they are recruited in.

In Chapter 3 I tested older adults with no apparent decline in attention switching and spatial planning abilities. Despite their good performance in the spatial planning and attention switching tasks, the older adults' overt attention was attracted by distractors, away from the otherwise preferred viewing location (the appearing point). Younger adults did not show this attentional bias. This suggests that older adults were less able to inhibit attentional capture towards task-irrelevant distractors, which is consistent with previous research (Crawford et al., 2013; Milham et al., 2002; Olincy et al., 1997). Hence, although EF subcomponents such as spatial planning and attention switching (as measured by BADS and RMA) seemed preserved in the older adults tested, cognitive speed (RMA latencies) and attentional control (inhibition of overt attentional capture) showed a decline. This is consistent with a differential decline of different executive subcomponents across ageing (Maldonado, Orr, Goen, & Bernard, 2020; Treitz et al., 2007) and recent finding showing that older adults can modulate their attention in the same way as younger adults (Hilton et al., 2019). D. Friedman, Nessler, Johnson Jr, Ritter, and Bersick (2007) using a task-switching paradigm, showed that on switch trials ERP components relating to task-set attention, re-allocation of attention, and conflict monitoring/detection were elicited for younger, but not older adults. Rather, the older adults' data were more

consistent with ongoing recruitment of executive processes when task demands did not require them to do so. D. Friedman et al. (2007) also interpreted their results in the context of selective breakdown of executive processes when resources required to implement them were over-taxed and compensation failed.

In Chapter 4 I found that although older adults could once again make safe crossing decisions as they left more TTI than younger adults. When cars travelled faster older and younger adults made riskier decisions compared to when cars travelled slower as both age groups reduced their TTI. However, older adults were more impacted than younger adults as they reduced their TTI by a larger amount than younger adults. It may be that these more complex situations of cars travelling quickly and from both directions require a larger cognitive load than the situation in Chapter 3 where cars only travelled along one direction. Therefore, the neural resource ceiling of the older adults may have been reached and so they are no longer able to compensate for their decline in functioning of the DLPFC. This may be why older adults are no longer able to perform at the same level as younger adults. Along with this, older adults with poorer executive functioning, specifically those with poorer spatial planning abilities, have reduced load capacity compared to those with better spatial planning abilities (Geraghty et al., 2016; Phillips et al., 2003). As older adults are hypothesised to cope with increased load by recruiting more neural resources, those older adults with poorer spatial planning abilities may have to recruit more neural resources at lower loads than older adults with better spatial planning due their reduced load capacity. Therefore, older adults with poorer spatial planning abilities may reach their resource ceiling earlier than older adults with better spatial planning abilities (Phillips et al., 2003). This may explain why older adults with poorer spatial planning abilities make riskier crossing decisions in more complex situations than older adults with better spatial planning abilities. As mentioned earlier, the compensatory hypothesis as the reason for older adults recruiting additional neural resources when performing the same tasks as younger adults is still debated in the literature (Morcom & Henson, 2018). Further research is required to determine the reasons older adults recruit these additional neural regions,

whether executive functioning abilities influence the level of and when additional neural regions are recruited, and finally why these additional regions are recruited.

### **6.2.2 Differences between visual and neural processing involved in naturalistic and lab based experiments**

As mentioned above I find similarities between the findings of psychophysics experiments and more natural stimuli, in that older adults and young children show increased capture of overt attention by distractors compared to younger adults and older children. There are a number of behaviours which traditional psychophysics studies are not able to investigate, but which can be investigated using natural stimuli. One example is during natural tasks the eye-movement system encounters different demands compared to sitting still in the laboratory. For example, smooth-pursuit eye-movements as performed in the real world are often accompanied by head movements and vestibular-ocular reflexes but not in a laboratory setting where head movements are often restricted (Niemann et al., 1999). In terms of brain regions, these additional movements recruit regions in the dorsal pathway (Bremmer et al., 2000), ventral intraparietal area (Bremmer et al., 2001, 2002; Britten, 2008; A. Chen et al., 2011; Wall & Smith, 2008), and the medial superior temporal area (Bremmer et al., 1999; Duffy & Wurtz, 1991; Gu et al., 2008; Pitzalis et al., 2013) which are involved in the processing of spatial information including self-motion and object motion signals. In my third study my participants made these head movements and vestibular-ocular reflexes as my participants would need to move their heads to monitor for cars coming from both directions. As my participants are making these head and eye movements they are likely to also be recruiting the additional neural regions mentioned above. Therefore the VR experiment that I have developed, a well controlled natural road scene which required participants to make head movements, may be the ideal type of experiment to investigate these additional eye movements. With the addition of an EEG or mobile EEG system this would also allow us to investigate the involvement of the dorsal pathway, ventral intraparietal area, and medial superior temporal area in attentional control, and how these areas

may change across the lifespan.

Alongside this, there are brain regions that are more active in the perception of natural scenes than in the perception of low-level stimuli, specifically the parahippocampal area, the retrosplenial cortex, and the transverse occipital sulcus, which form part of the scene processing network (Aguirre, Detre, Alsup, & D'Esposito, 1996; Aguirre, Zarahn, & D'Esposito, 1998; Bar & Aminoff, 2003; Epstein & Kanwisher, 1998; Grill-Spector, 2003; Hasson, Harel, Levy, & Malach, 2003; Ishai, Ungerleider, Martin, Schouten, & Haxby, 1999; Maguire, 2001; Nasr et al., 2011). Furthermore, these regions have been suggested to be involved in encoding and recognition of environmental scenes (Aguirre et al., 1996), as well as episodic memory, navigation, imagining future events (Spreng, Mar, & Kim, 2009; Vann, Aggleton, & Maguire, 2009). As they are involved in memory of scenes and imagining future events they may be involved in road crossing scenes, first in the encoding of the scene, but also when cars travel along both lanes. Participants will need to attend to one direction, turn their heads and attend to the other direction while remembering where the cars were on the first direction, imagining and calculating the future trajectory of the cars. Moreover, these regions are not fully mature in young children (Jiang et al., 2014) and therefore may influence how children perceive and interact with the world around them. Further research should be done to investigate the role of the scene processing network in day to day activities, such as road crossing, and how maturation of these areas might influence this potential role. Virtual reality experiments such as the one in Chapter 4 may be ideal to study regions such as the scene processing network as these experiments allow for dynamic scene perception but with the ability to control and manipulate all aspects of the scene to see how this influences activity and functioning in the scene processing network.

### **6.2.3 Specific insights gained from a combined data-driven and hypothesis-driven approach**

Throughout this thesis I have taken a combined hypothesis and data-driven approach. Each method has its benefits and limitations but a full review is beyond the

scope of this paper (see Voit, 2019 and Kell & Oliver, 2004 for a review). An advantage of hypothesis driven approaches is that they are rigid, exact, and have clear guidelines for how to validate the experiments (Voit, 2019). However, hypothesis-driven research is biased by the experimenter as hypotheses are selected based on the limited knowledge the experimenter has of the field which can lead the experimenter away from unexpected but true hypotheses (Kell & Oliver, 2004; Van Helden, 2013; Voit, 2019). Data-driven research has less bias than hypothesis-driven approaches as they explore large amounts of data with the aims to spot patterns or correlations within the data without specific hypotheses (Kell & Oliver, 2004; Van Helden, 2013; Voit, 2019). However, data-driven research does not have defined methods for validation and due to the large volume of data the results can often be difficult to interpret (Voit, 2019). A combined approach could lead to the best of both worlds. For example Kell and Oliver (2004); Van Helden (2013) and Voit (2019) suggest a data-driven approach can be taken initially to examine large amounts of data free of bias to find specific patterns in the data. These patterns can then be used to formulate specific hypotheses which can be tested to determine why these patterns arise in the data. The combined approach is the direction I have taken which has allowed me to find novel insights I might not have found otherwise and allowed me to asked specific questions as a result of these findings. I will go through examples of this approach below.

In Chapter 2 there was little previous literature on where individuals look when they cross the road and how this changes during development. With little previous literature it would be difficult to formulate a well defined unbiased hypothesis about where participants look. Therefore, for the analysis of the eye tracking data it did not make sense to use a hypothesis driven approach, such as an area of interest analysis. Moreover, an area of interest analysis involves subjective segmentation of the stimulus space which can lead to problems such as engendering natural variations across authors (Caldara & Mielliet, 2011). In some cases this can lead to difficulty in generalizing observations across studies (Caldara & Mielliet, 2011). Areas of interest are also in danger of circular analysis and “double-dipping” – the use of the same

dataset for selection and selective analysis (Caldara & Miellat, 2011; Kriegeskorte, Simmons, Bellgowan, & Baker, 2009). Had I taken an area of interest approach for the analysis of the eye tracking data I would have missed the finding that 5-10y/o children look further down the road than the appearing point when traffic density was high. Based on previous literature the areas of interest chosen would be the section of the road closest to the participants, and the section of the road slightly left of the closest point to the participants all the way to the appearing point, as used used by Tapiro et al. (2016). By not splitting the area of interest covering the left section of the road it would be impossible to differentiate between when participants looked at the appearing point and when they looked further down the road. Therefore, the finding that children looked further down the road than the appearing point when traffic density was high would have been missed.

The data-driven eye tracking findings from Chapter 2 and Chapter 3 allowed me to formulate specific hypotheses and design an experiment to address these hypotheses in Chapter 5. In Chapters 2 and 3 I found that younger adults looked predominantly at the appearing point and did not overtly follow the cars down the road. This finding suggested a potential dissociation between overt and covert attention. This suggestion became my hypothesis for the experiment in Chapter 5. However, even in Chapter 5 I could not take a wholly hypothesis-driven approach with the EEG analysis. A hypothesis-driven peak analysis would not have allowed me to identify the time point when the drop in the 30Hz power occurred, indicating a dissociation of covert and overt attention. Therefore, I took a data-driven approach with the EEG analysis so that I would be able to identify the point at which the division of attention occurred.

Similarly, in Chapter 4 a predominantly hypothesis-driven approach was more beneficial. Based on the findings in Chapter 3 and by Oxley et al. (1997) there was a suggestion that older adults may have more difficulties making crossing decisions when cars travelled from both directions than when cars travelled from one direction. Therefore, I decided to assess whether there was a difference in the crossing decisions and eye movements of older and younger adults when cars travelled from both

directions compared to when they travelled from just one direction. However, older adults have also been shown to have more difficulties when cars travelled along the near lane compared to the far lane (Geraghty et al., 2016; Oxley et al., 1997, 2005). This finding meant that there was a confound in comparing crossing decisions when cars travelled from one lane and one direction to crossing decisions when cars travelled from two lanes and two directions. I would be unable to identify whether any effect that arose from cars travelling from both directions came as a result of cars travelling in the far lane, from two lanes, or from both directions. Therefore, I split the study in Chapter 4 into two experiments with the first experiment addressing this confound. Had I taken a data-driven approach I would have had a general hypothesis of examining the impact of cars travelling from both directions and then looked at the road crossing decisions and eye movement data to find any patterns. I would have found differences between road crossing decisions on the two conditions but not have been able to identify whether the effect was due to cars coming from both directions, both lanes, or the far lane.

In sum, a combined hypothesis and data-driven approach allowed me to maintain a high level of experimental design to ensure I was answering the research questions I sought to answer but also allowed me to be open to unexpected findings that might have otherwise been missed.

#### **6.2.4 Contributions to the road safety literature and recommendations to improve road safety**

Alongside the attentional control contributions, my research has strong practical implications for road safety. In Chapter 2 I found that the optimal viewing location for making safe crossing decisions was the vehicle appearing point. I also found that children were distracted by pedestrians and they followed the cars down the road when traffic density was high. This suggests that younger children do not know where they should be looking when crossing the road. These findings can be used to update existing government safety campaigns such as the such as the stop, look, and listen campaign (Department for Transport, 2020). This campaign message

indicates that children should look at the road but not where on the road they should be looking. My findings allow us to improve road safety training programs for children by adding that children should look at the appearing point and try to ignore distractors such as other pedestrians. This could be achieved by contacting the UK Department for Transport and working with them to develop new lesson plans, games and films which include where children need to look at a road crossing. These lesson plans can then be used to train children on appropriate crossing behaviour and assess whether these new lesson plans are more effective than the previous ones. If so, they could be rolled out in schools or given to parents to assist them in teaching their children safe crossing behaviour. Finally, road safety campaigns and advertisements can be updated to say not only that children should look at the road but where they should be looking.

In regards to older adults, I found that they have difficulties making safe crossing decisions when cars travelled quickly. Training older adults to improve their attentional control ability in road crossing situations may be less effective for older adults for children as their neural processes will continue to decline while children's processes will continue to mature. Therefore, infrastructure changes may be more appropriate to improve the safety of older adults. The guidance in where to put speed limits could be updated so that speed limits are placed around nursing, and care homes, as well as retirement villages. In contrast to schools, this suggestion is not currently in the guidance on where to put speed limits (Department for Transport, 2012).

I also found that older adults have difficulties when cars travelled from an obscured view. Another infrastructure change, along with speed limits, would be to make sure all pedestrian walkways, particularly designated crossing locations, are clear of vegetation or any form of object that obscures the view of oncoming cars.

### **6.2.5 Summary of contributions to visual attention and cognitive neuroscience literature**

More than the potential contribution to road safety campaigns, my research contributes to the visual attention and cognitive neuroscience literature. I show for the first time that the critical age of 10 y/o for children's ability to inhibit distractors applies in not only a naturalistic task but a task children perform everyday. I also showed in a data-driven way that premature attentional control skills which caused deficits in distractor inhibition, had a large impact on day to day activities for children as they made riskier crossing decisions than younger adults. I show for the first time in an experiment that was designed to capture a simple, everyday situation that older adults are able to overcome their general slowness and attentional capture by distractors and make safe crossing decisions. However, in more complex situations older adults are no longer able to overcome their cognitive decline and make riskier decisions. To come to these findings I have developed new methodological techniques such as a novel algorithm to parse smooth pursuit eye movements during a free-viewing task from monocular eye tracking data. This algorithm can be applied to any eye tracking task and opens the door to more detailed study of specific eye movement parameters during naturalistic tasks. I also developed an SSVEP paradigm which allowed us to investigate the role of overt and covert attention in a divided attention paradigm. This paradigm can be modified and used in a large number of tasks to investigate the involvement of covert attention in everyday tasks.

## **6.3 Future directions**

As mentioned above, older children, younger adults, and high functioning older adults preferentially use the appearing point of the vehicles and do not overtly follow the cars down the road. The question remains whether these participants' overt and covert attention is focused on the appearing point for the duration of the time they are overtly attending to the appearing point or whether there is a dissociation

between overt and covert attention where participants' are overtly attending the appearing point and covertly monitoring the cars travelling down the road. To investigate this question I intend to use the SSVEP and eye tracking approach I developed in Chapter 5 but modify the experiment to more directly address this question. I will have participants attend to the appearing point which flickers at one frequency, while having a moving object, acting as the vehicle moving down the road, move across the screen flickering at a different frequency. Participants would be instructed to perform the same task as in the road crossing experiment, where they press a button to indicate when they think it would be safe to cross the road. If participants solely focused on the appearing point their gaze would be focused on the appearing point, and their SSVEP signal would be at the same frequency as the object at the appearing point. If participants overtly attended to the appearing point but covertly attended to the moving object I would expect their gaze to be on the appearing point but their SSVEP signal to be at the frequency of the moving object rather than the object at the appearing point.

To further investigate the hierarchical processes involved in the perception and processing of natural visual stimuli during a day to day task such as road crossing I plan to use neural networks. I plan to use these neural networks to model which aspects of the visual system (earlier or later visual areas) drive gaze behaviour and how this differs between children, younger adults, and older adults. I plan on doing this in a similar way to that done by Lindh, Sligte, Asseconi, Shapiro, and Charest (2019). They presented a pre-trained neural network with images of different objects and human faces and it categorised them into different object categories such as face, ball, etc. The different layer or 'neural' activations from the neural network are used to predict the behavioural data for participants performing an attentional blink experiment. The aim of this was to determine whether earlier or later layers of the visual cortex were more predictive of human behaviour. The neural network they used was constructed such that the layers were similar to the hierarchical layer structure in the visual cortex. Therefore, if neural activations in earlier computational layers were more predictive of behaviour it would suggest that

perhaps earlier layers of the human visual cortex would be more responsible for the behaviour shown by participants. This hypothesis could then be tested using neuroimaging experiments. To apply this to my research I would construct a similar neural network but trained on videos rather than still images. I would then take the neural activations and predict the behavioural and eye movements results. The layer that shows the strongest prediction would be the layer to investigate within neuroimaging studies. This would allow us to formulate more precise questions to be used in fMRI studies to determine which aspects of the visual system are involved in making crossing decisions, and how declines in these areas influence crossing behaviour.

Given that I now have an understanding as to what aspects of attentional control influence children and older adults ability to make safe crossing decisions the next step would be to determine whether children's attentional control in these situations could be improved. Previous studies have shown that children's ability to make safe crossing decisions can be trained by training them in hazard perception (Schwebel, Combs, Rodriguez, Severson, & Sisiopiku, 2016; Thomson & Whelan, 1997; Zeuwts, Vansteenkiste, Deconinck, Cardon, & Lenoir, 2017), identifying safe places to cross (Thomson et al., 1992), or through parental guidance (Limbourg & Gerber, 1981). I could improve these training programs to include where children need to be looking before making a decision to cross the road. Based on my results that older children and younger adults focus their attention on the appearing point, distractors do not capture their attention, and that these groups of pedestrians are among the safest (BITRE, 2015; ERSO, 2018; World Health Organization, 2015) I suggest that the appearing point is an important location for participants to focus their attention to make decisions on whether it is safe to cross. Therefore, these training programs could have young children focusing their attention on the appearing point and practising to inhibit their attentional capture by distractors. Further research would be required to determine if children are able to learn this behaviour and then if it is effective at improving children's safety at road crossings.

For older adults, it may not seem immediately possible to improve older adults'

visual attentional control skills as the neural mechanisms behind them will continue to decline. Some studies have shown that with practice (Bojko, Kramer, & Peterson, 2004) or with a change of strategy (Becic, Boot, & Kramer, 2008) older adults are able to improve their control of eye movements or search strategy and in turn improve their performance (Becic et al., 2008; Bojko et al., 2004). Therefore, if I are able to instruct older adults in which attentional control strategy to use, specifically that of focusing on the appearing point and inhibiting attentional capture by distractors, older adults might be able to take this on as in Becic et al. (2008) and perhaps improve their performance. Further research would need to be done to assess if it would be possible to train older adults on the optimal strategy to use and if this improves the safety of older adults in road crossing situations.

## 6.4 Concluding comments

To conclude, the research in this thesis used novel approaches to address the socially relevant and timely question of pedestrian safety. To this aim, I used a variety of methods ranging from eye-tracking to image processing, EEG and virtual reality, and I developed new techniques tailored to the questions at hand. For the first time, I directly investigated the relationships between visual exploration, road crossing decisions and changes in attentional control through the lifespan. My findings showed that children below the age of 10 are less able to inhibit attentional capture by distractors, which increased the risk of unsafe crossing decisions. In similar, simple situations, older adults also show an attentional bias towards distractors, but they maintain the ability to make safe crossing decisions. Virtual reality experiments with systematic manipulations of the complexity of the road crossing scene revealed that older adults make riskier crossing decisions in specific situations such as when cars travel quickly, or from different directions. This research furthers our understanding of attentional control through the lifespan as well as providing insights for pedestrian safety. As such, it provides avenues for the development of training and safety guidelines for pedestrians.

Together these studies indicate several potential attentional control mechanisms

involved in natural scene perception, and that they impact on our day to day functioning. These indications point towards directions for future research investigating which neural mechanisms and in what way these neural mechanisms are involved in natural scene perception, and how they impact on day to day functioning. Moreover, my research highlights the role that cognition and visual perception play for traffic accidents, particularly those involving children. My research provides avenues to improve upon current training methods and develop new training methods to improve the safety of young children and older adults in road crossings. Moreover, my research points towards certain infrastructure changes such as more widespread speed limits to improve the safety of vulnerable pedestrians.

# Appendix A

## Supplementary materials for chapter 2

### A.1 Supplementary Figures

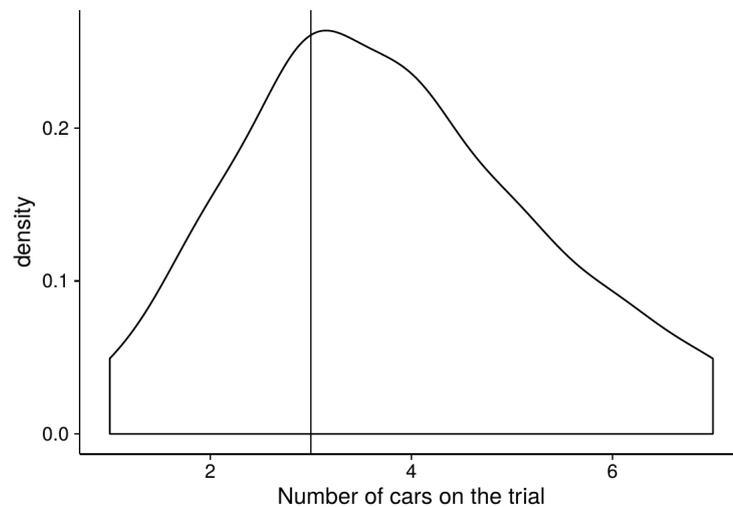


Figure A.1: **Density of trials with each number of cars present.** The kernel density plot shows the density of trials with each number of cars present, ranging from 1 to 7 cars present in a trial. The figure was used to determine 'high traffic' and 'low traffic' density trials, to assess the influence of traffic density on the low level eye movement parameters (the number of fixations, durations of pursuits, etc). The peak of the kernel density appears at 3 cars present on the trial. From this I labelled 3 cars in the trial or fewer to be low traffic density and more than 3 cars in the trial to be high traffic density.

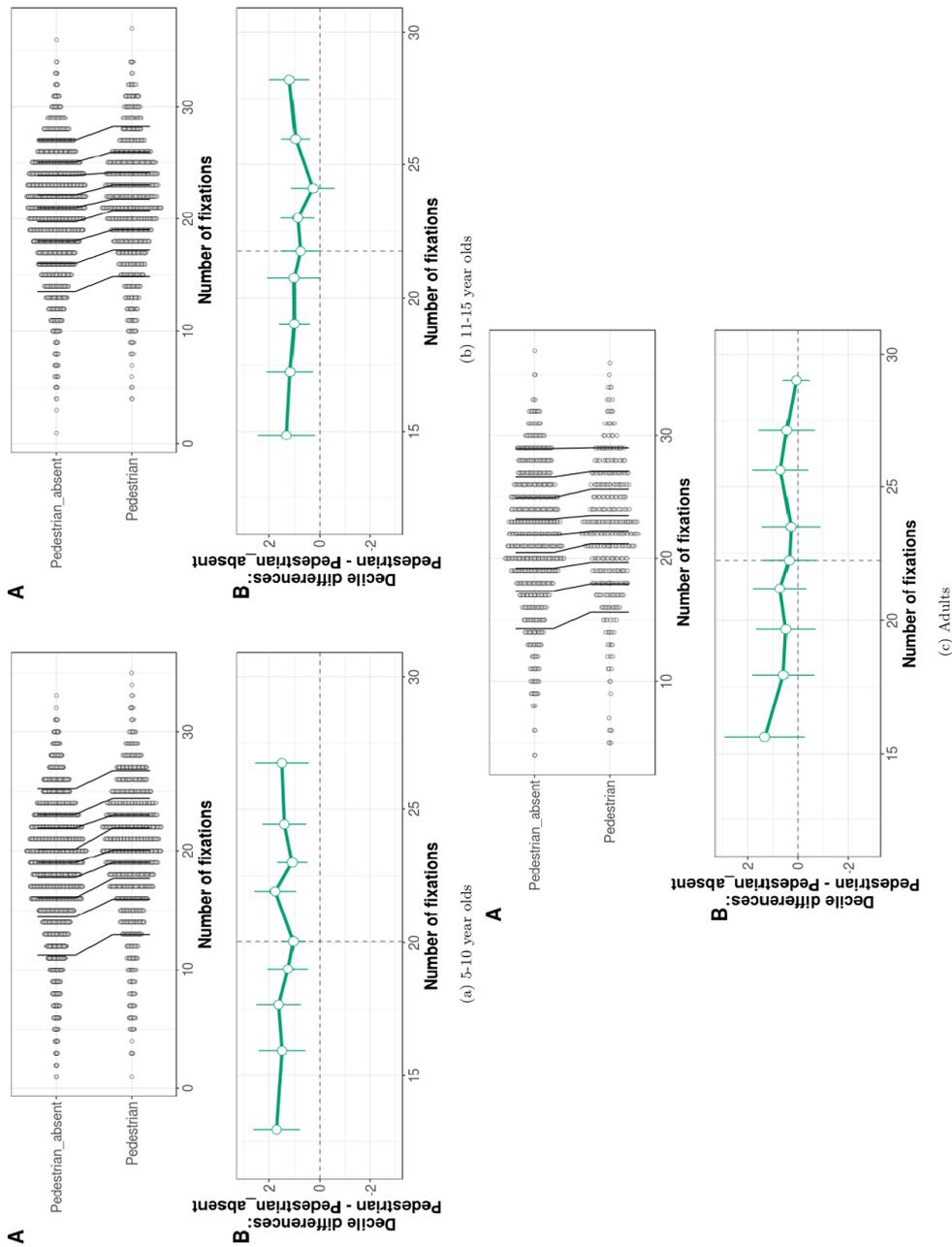


Figure A.2: **Shift functions for number of fixations with pedestrian presence** Panel A for each figure indicates scatter plots for the number of fixations in trials – the points are jittered by their local density. The black lines indicate the estimated deciles for each group, as well as the difference between them. Panel B for each figure shows the shift function for the two distributions. The shift functions show the difference between the number of each gaze sample type for each decile – white discs – on trials where pedestrians are present and trials where pedestrians are not present. The error bars indicate 95% confidence intervals. A significant difference is present when the error bars do not include zero. (a) shows the difference in the number of fixations for 5-10y/os, (b) for 11-15y/os, and (c) for adults on trials where pedestrians are present and trials where they are not present. For more details on the shift functions see: Rousselet et al. (2017).

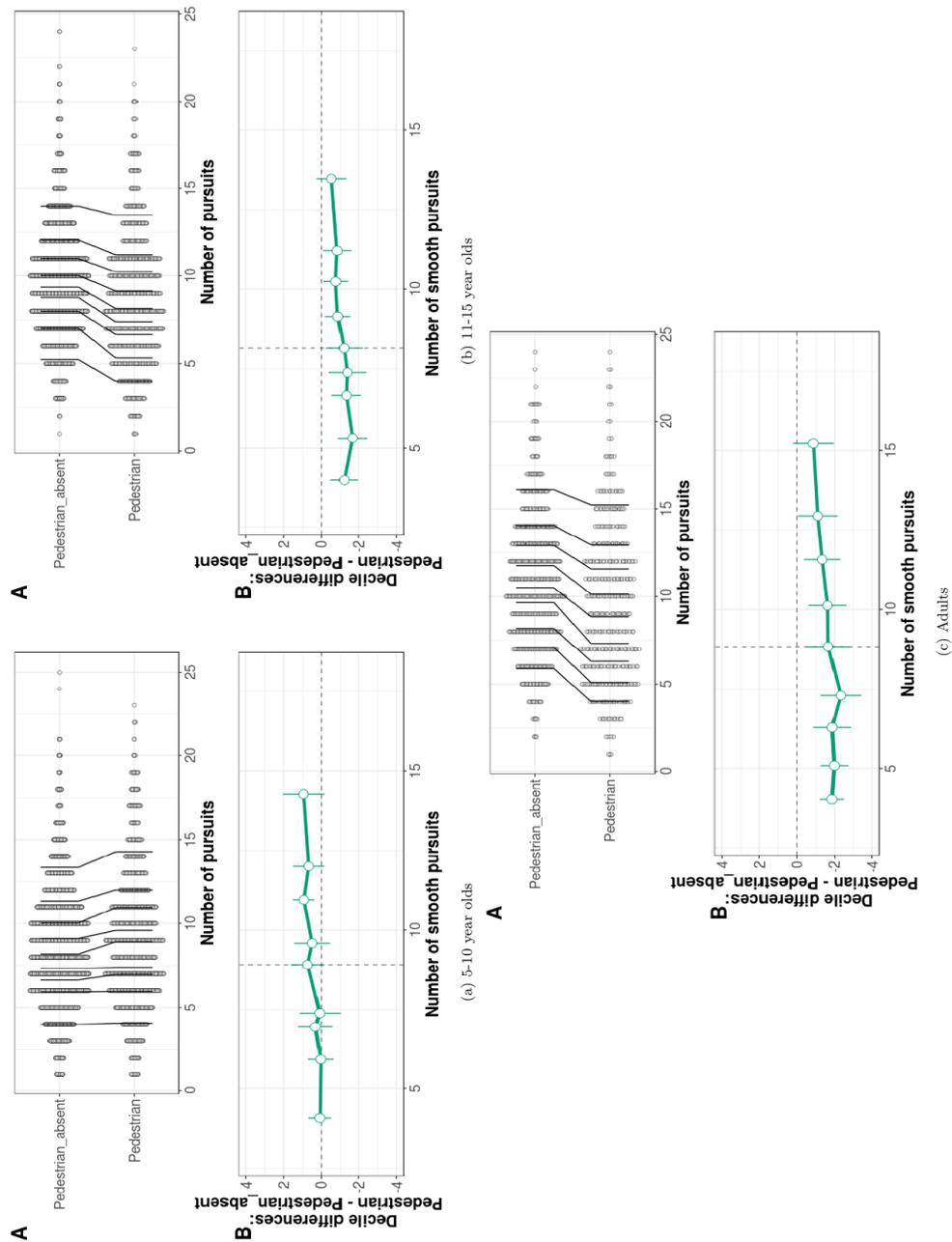


Figure A.3: **Shift functions for the number of smooth pursuits with pedestrian presence** (a) shows the difference in the number of smooth pursuits for 5-10y/os, (b) for 11-15y/os, and (c) for adults on trials where pedestrians are present and trials where pedestrians are not present.

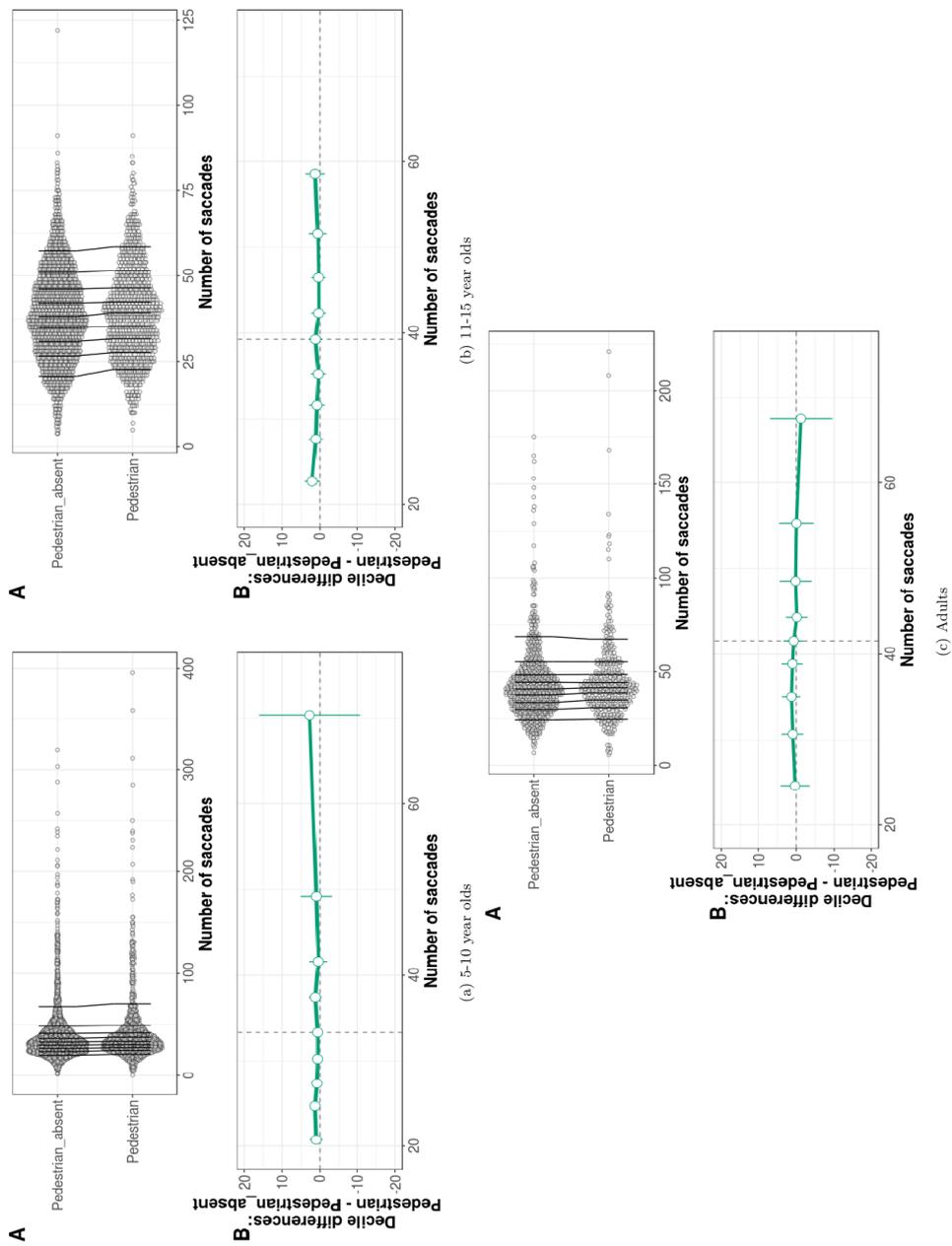


Figure A.4: **Shift functions for the number of saccades with pedestrian presence.** (a) shows the difference in the number of saccades for 5-10y/os, (b) for 11-15y/os, and (c) for adults on trials where pedestrians are present and trials where pedestrians are not present.

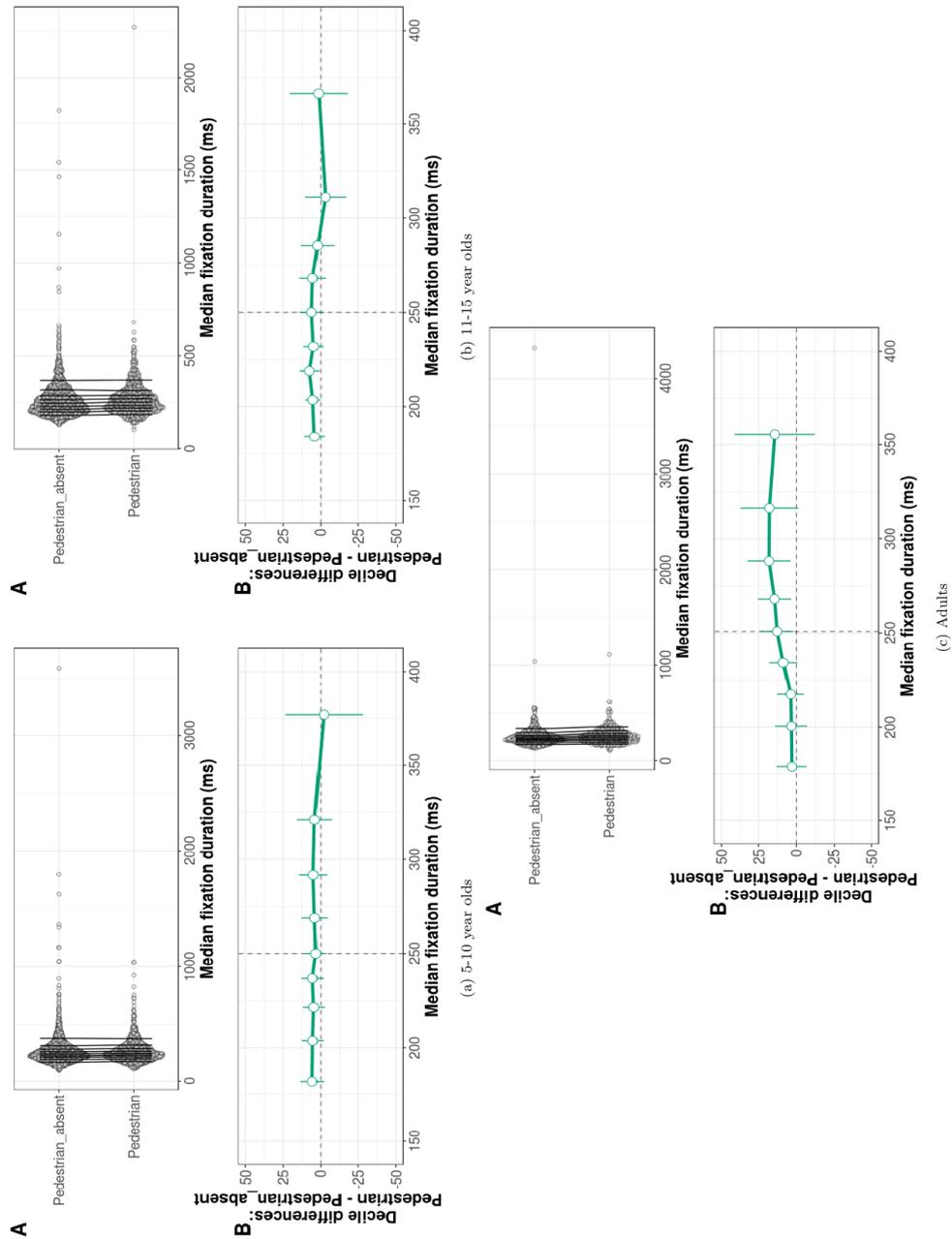


Figure A.5: **Shift functions for the median duration of fixations with pedestrian presence.** (a) shows the difference in the median duration of fixations for 5-10y/os, (b) for 11-15y/os, and (c) for adults on trials where pedestrians are present and trials where pedestrians are not present

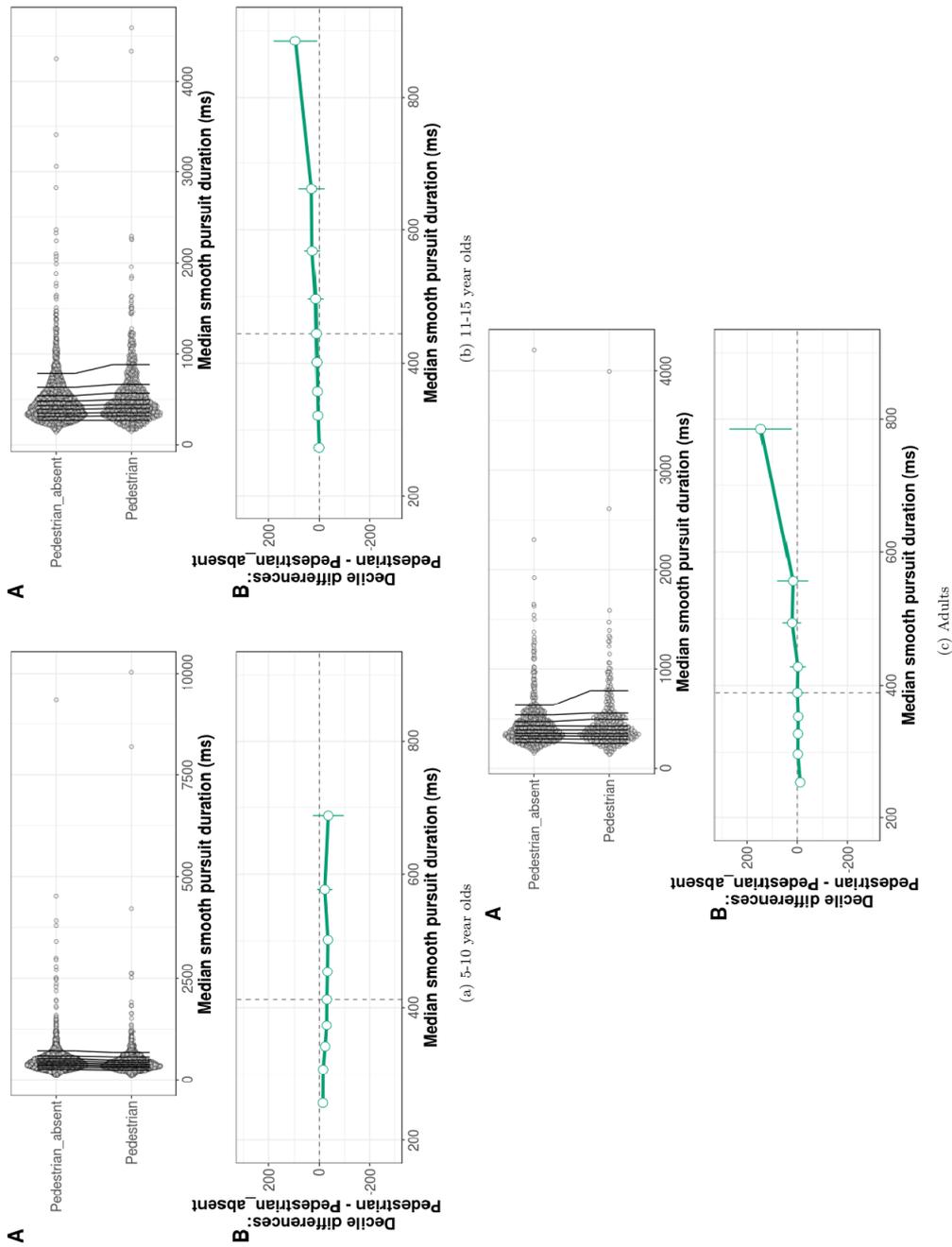


Figure A.6: Shift functions for the median duration of smooth pursuits with pedestrian presence. (a) shows the difference in the median duration of smooth pursuits for 5-10y/os, (b) for 11-15y/os, and (c) for adults on trials where pedestrians are present and trials where pedestrians are not present.

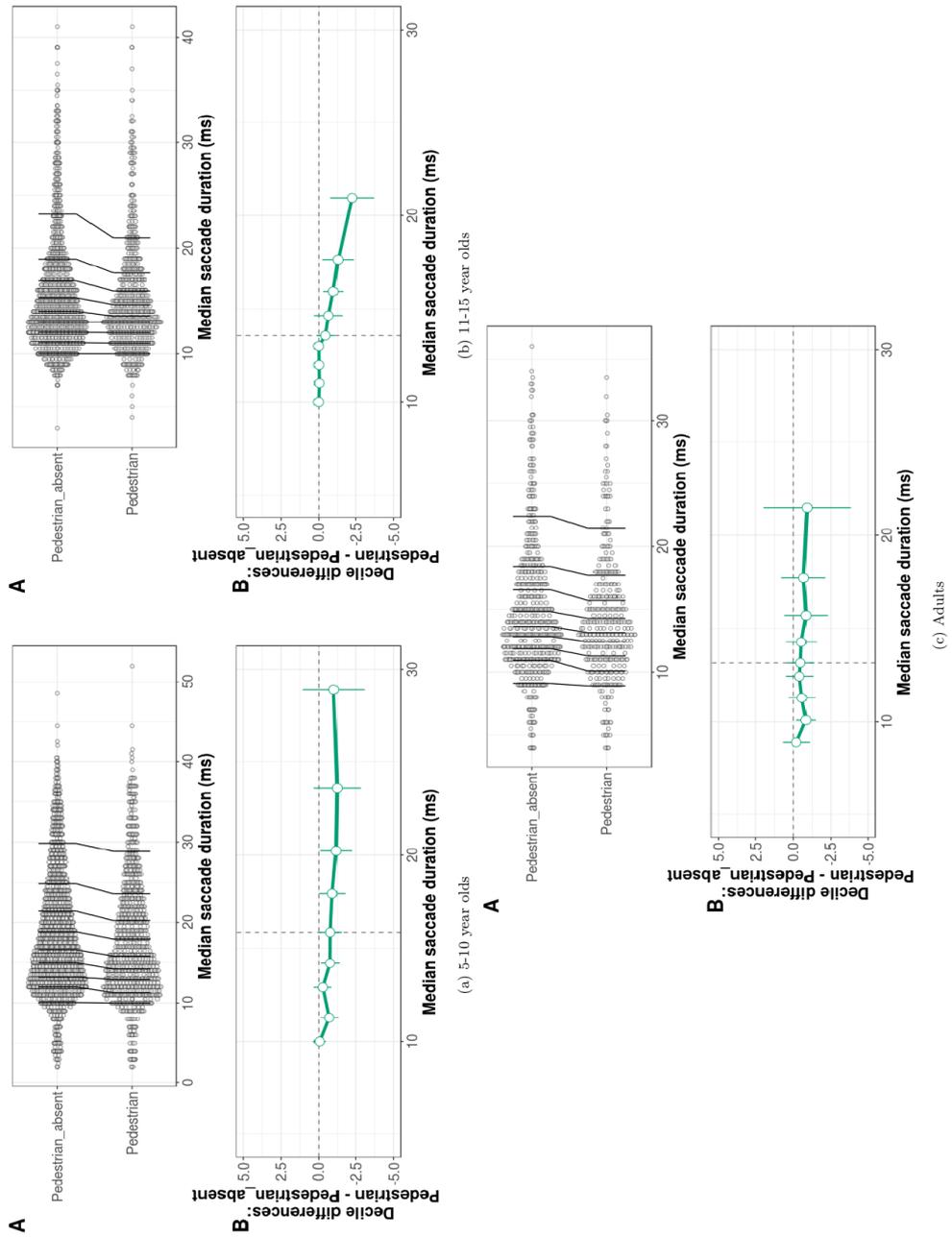


Figure A.7: **Shift functions for the median duration of saccades with pedestrian presence.** (a) shows the difference in the median duration of saccades for 5-10y/os, (b) for 11-15y/os, and (c) for adults on trials where pedestrians are present and trials where pedestrians are not present.

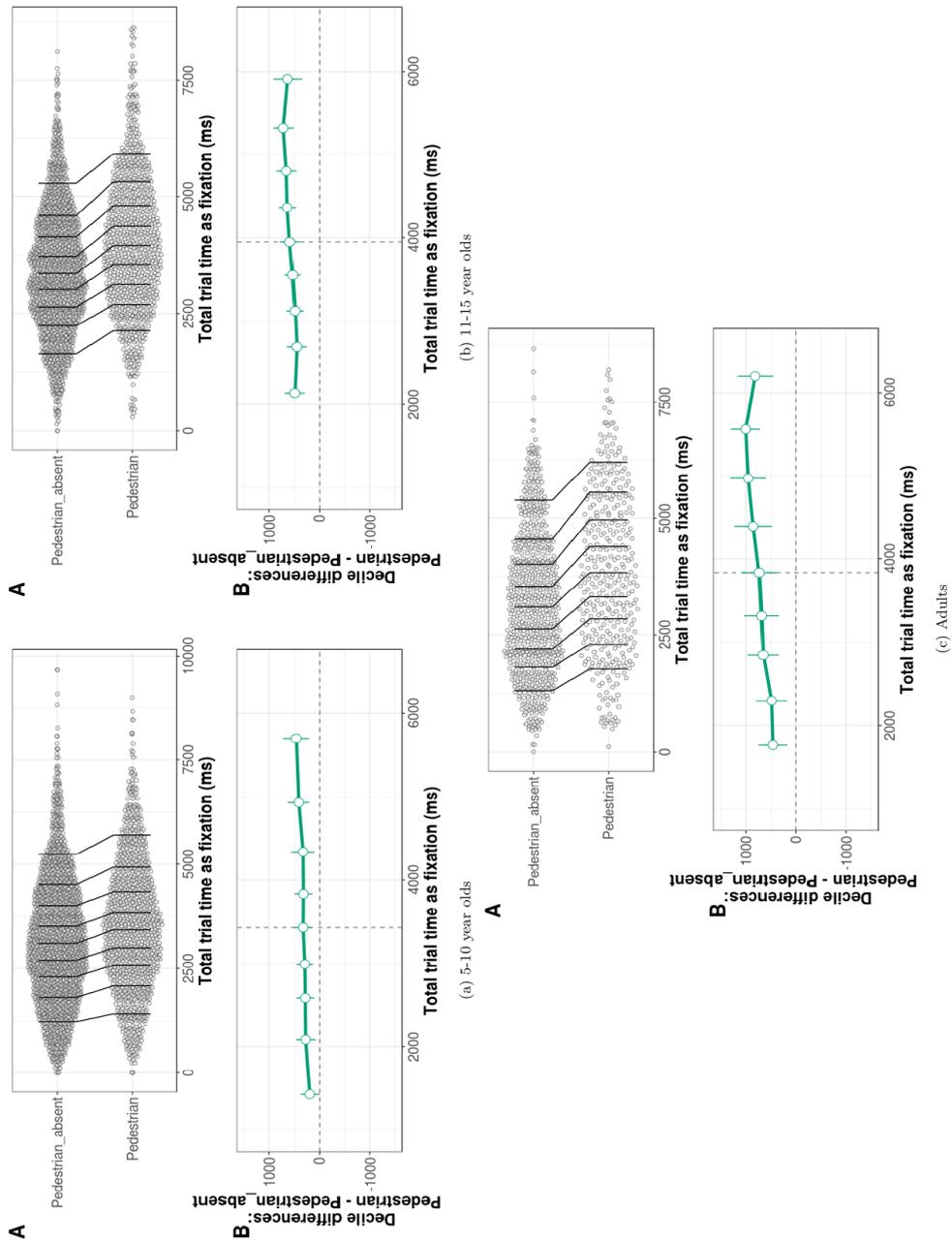


Figure A.8: **Shift functions for the proportion of trial time as fixation with pedestrian presence** (a) shows the difference in the proportion of trial time as fixation for 5-10y/os, (b) for 11-15y/os, and (c) for adults on trials where pedestrians are present and trials where pedestrians are not present.

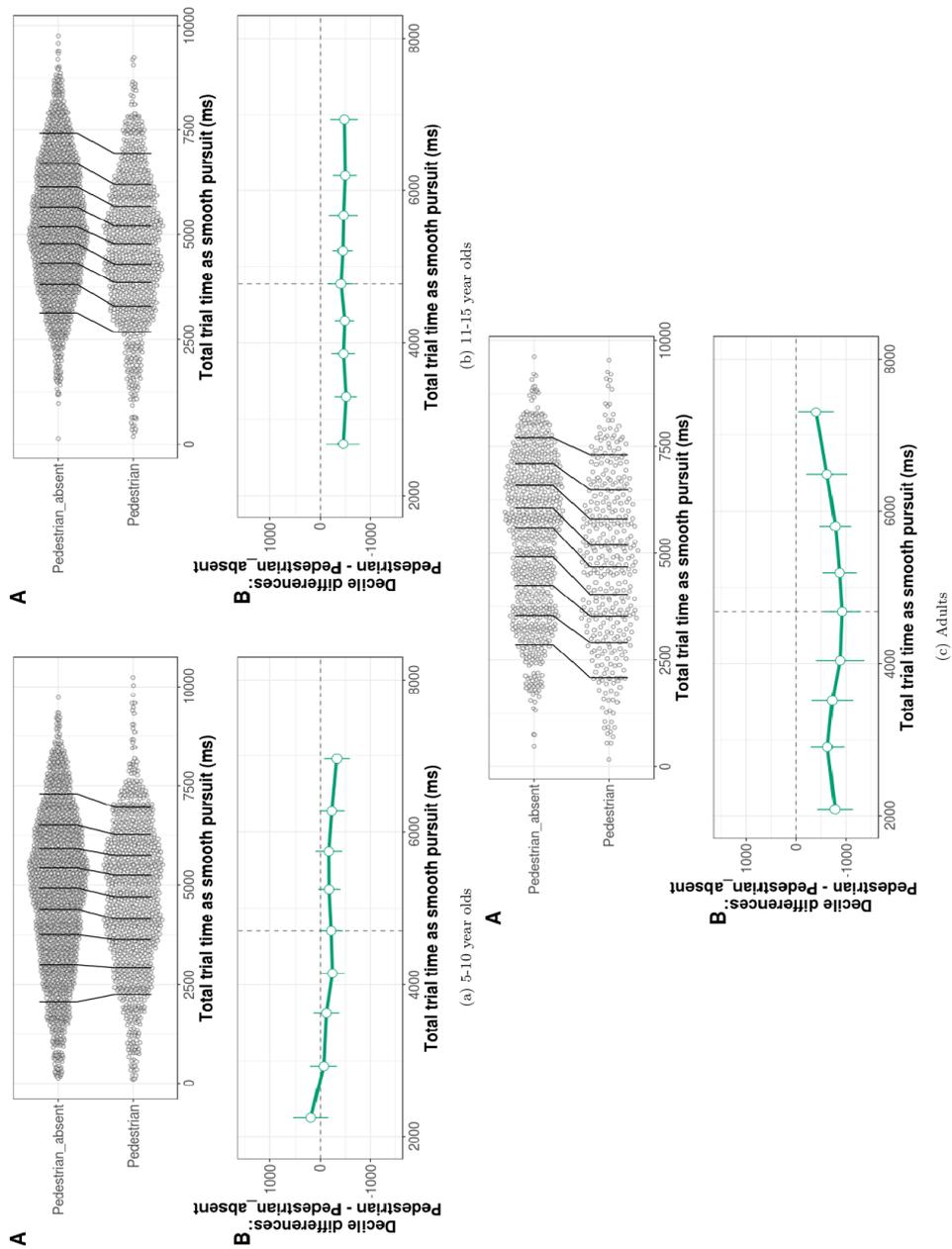


Figure A.9: **Shift functions for the proportion of trial time as smooth pursuit with pedestrian presence** (a) shows the difference in the proportion of trial time as smooth pursuit for 5-10y/os, (b) for 11-15y/os, and (c) for adults on trials where pedestrians are present and trials where pedestrians are not present.

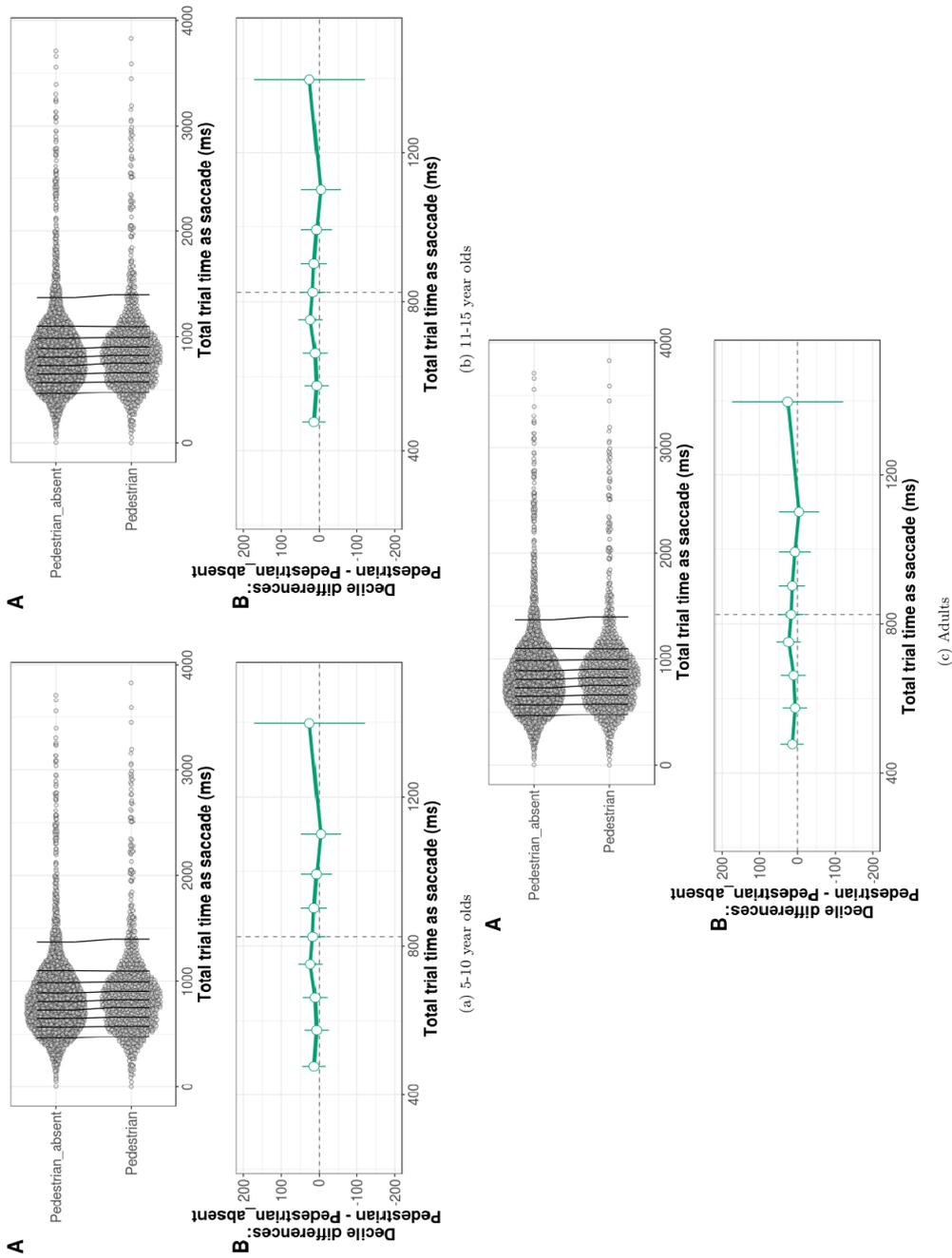


Figure A.10: **Shift functions for the proportion of trial time as saccades with pedestrian presence** (a) shows the difference in the proportion of trial time as saccades for 5-10y/os, (b) for 11-15y/os, and (c) for adults on trials where pedestrians are present and trials where pedestrians are not present.

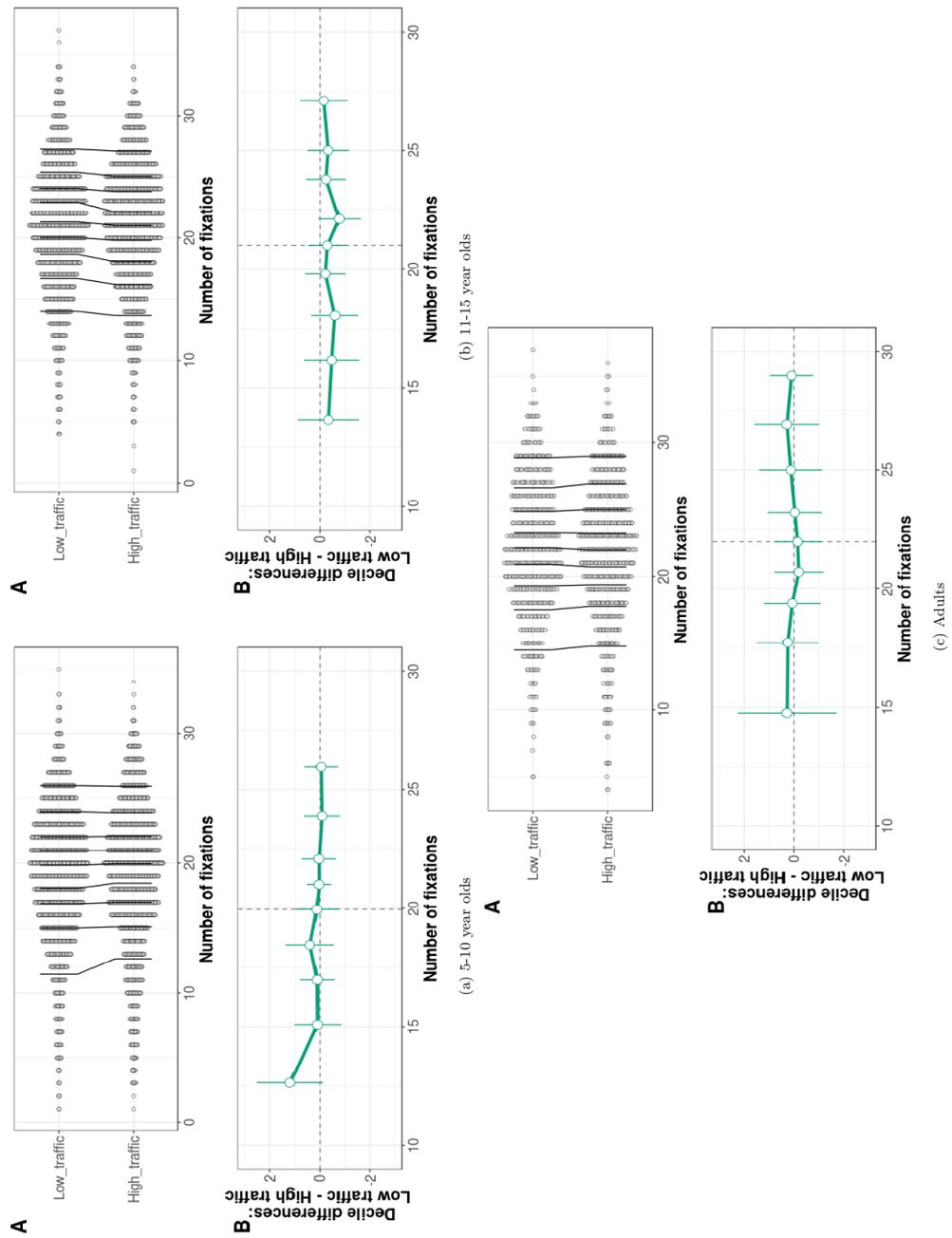


Figure A.11: **Shift functions for the number of fixations with traffic density** (a) shows the difference in the number of fixations for 5-10y/os, (b) for 11-15y/os, and (c) for adults on trials with low and high traffic density.

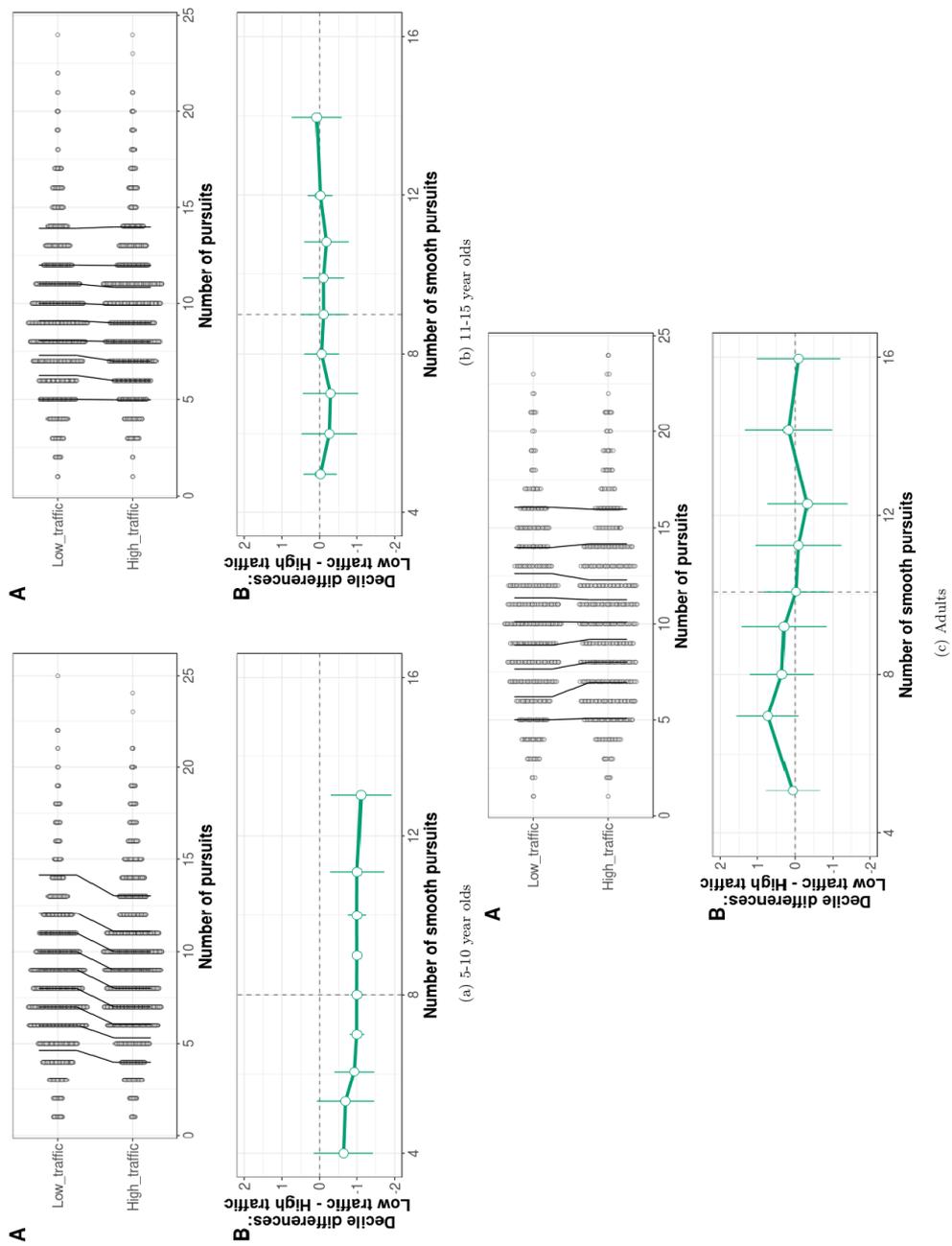


Figure A.12: **Shift functions for the number of smooth pursuits with traffic density** (a) shows the difference in the number of smooth pursuits for 5-10y/os, (b) for 11-15 y/os, and (c) for adults on trials with low and high traffic density.

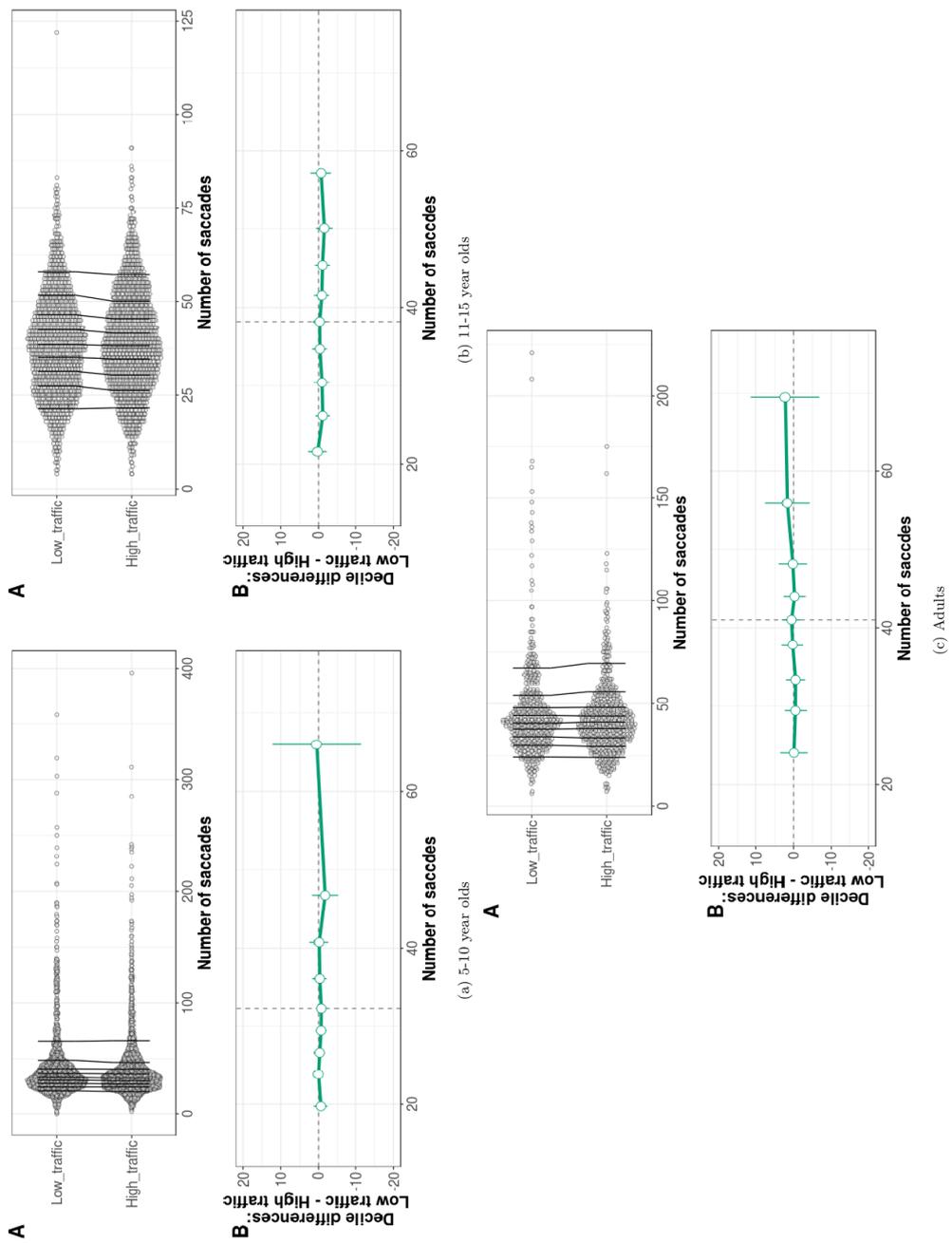


Figure A.13: **Shift functions for the number of saccades with traffic density** (a) shows the difference in the number of saccades for 5-10y/os, (b) for 11-15y/os, and (c) for adults on trials with low and high traffic density.

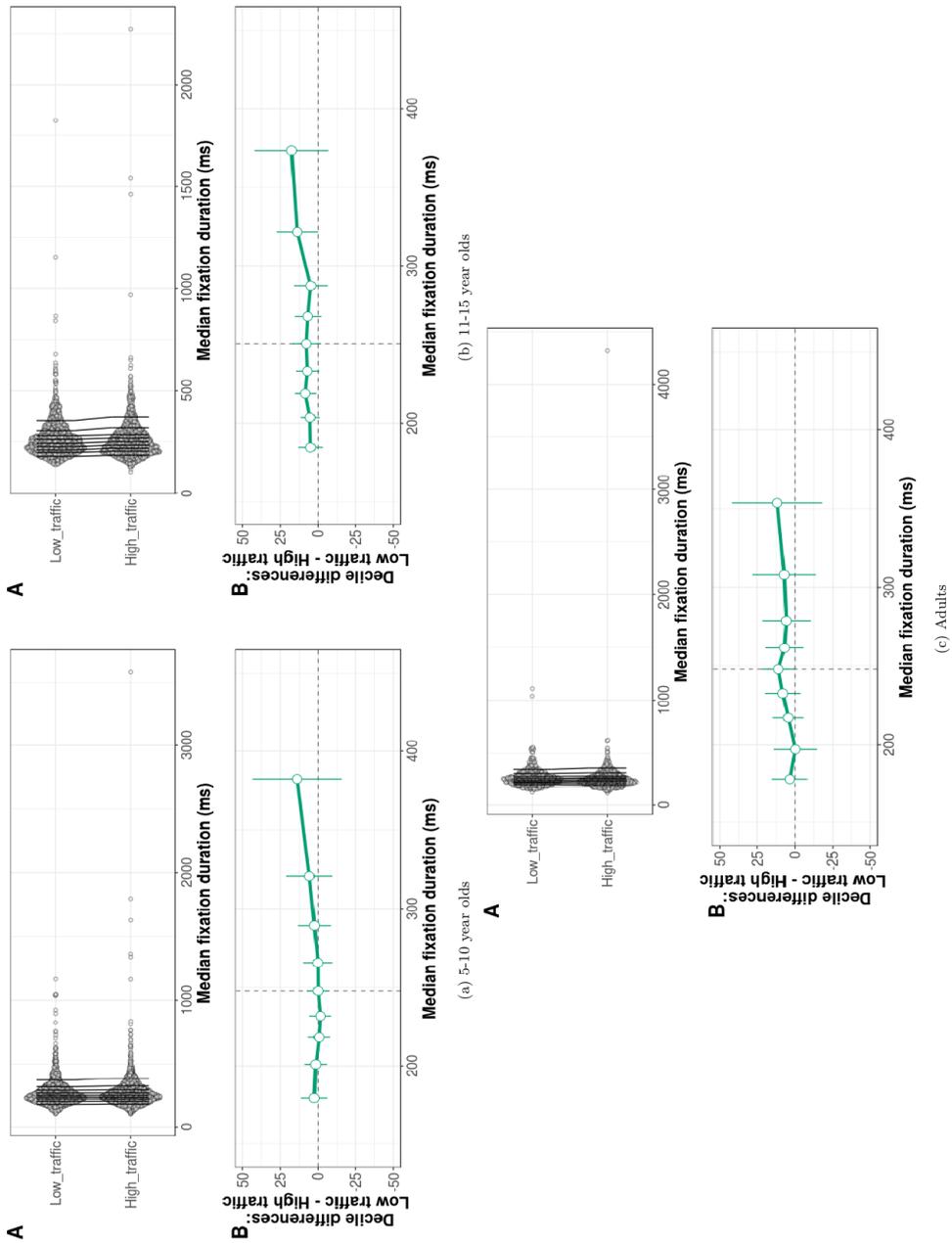


Figure A.14: **Shift functions for the median fixation duration for traffic density** (a) shows the difference in the median fixation duration for 5-10y/os, (b) for 11-15y/os, and (c) for adults on trials with low and high traffic density.

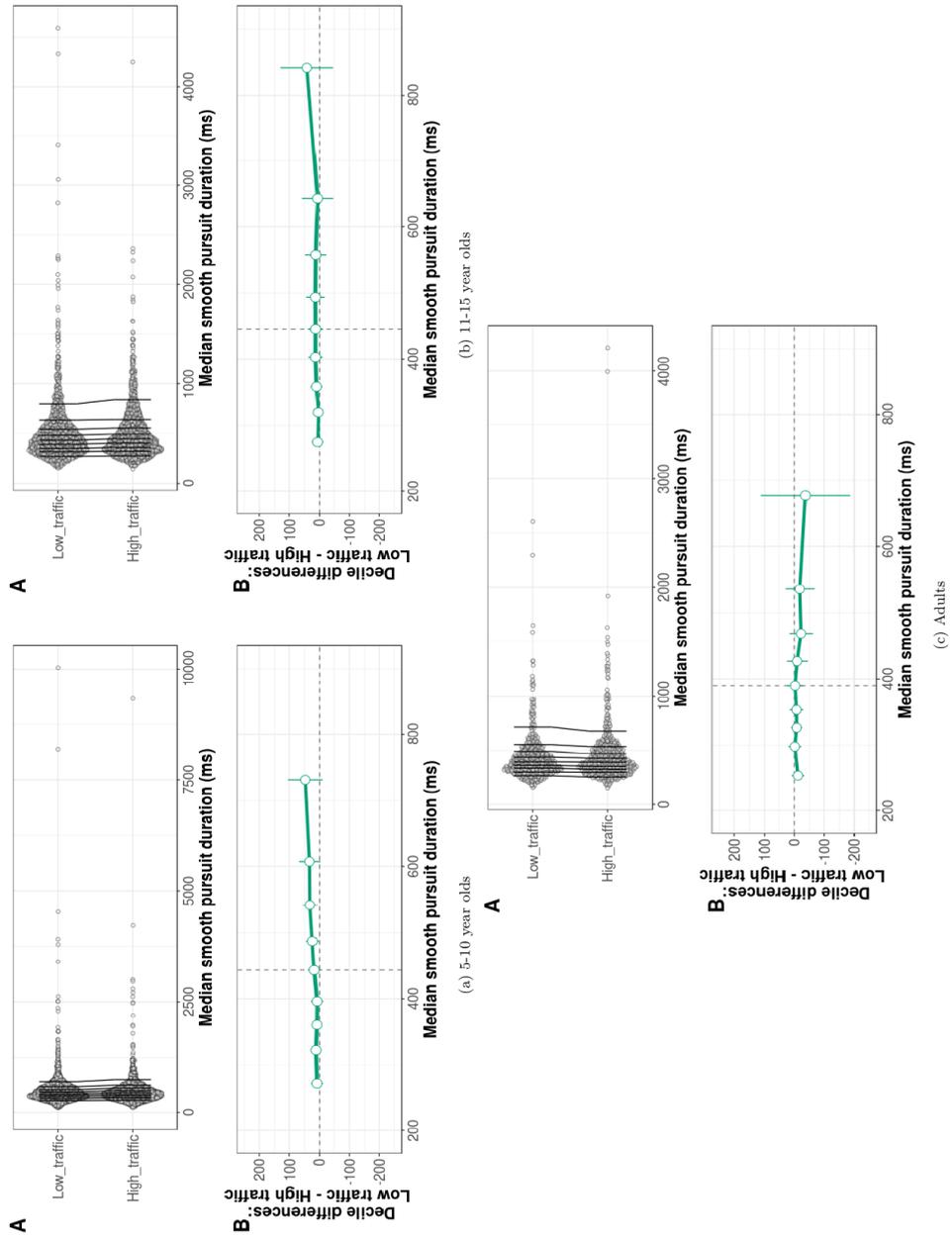


Figure A.15: **Shift functions for the median smooth pursuit duration for traffic density** (a) shows the difference in the median smooth pursuit duration for 5-10y/os, (b) for 11-15y/os, and (c) for adults on trials with low and high traffic density.

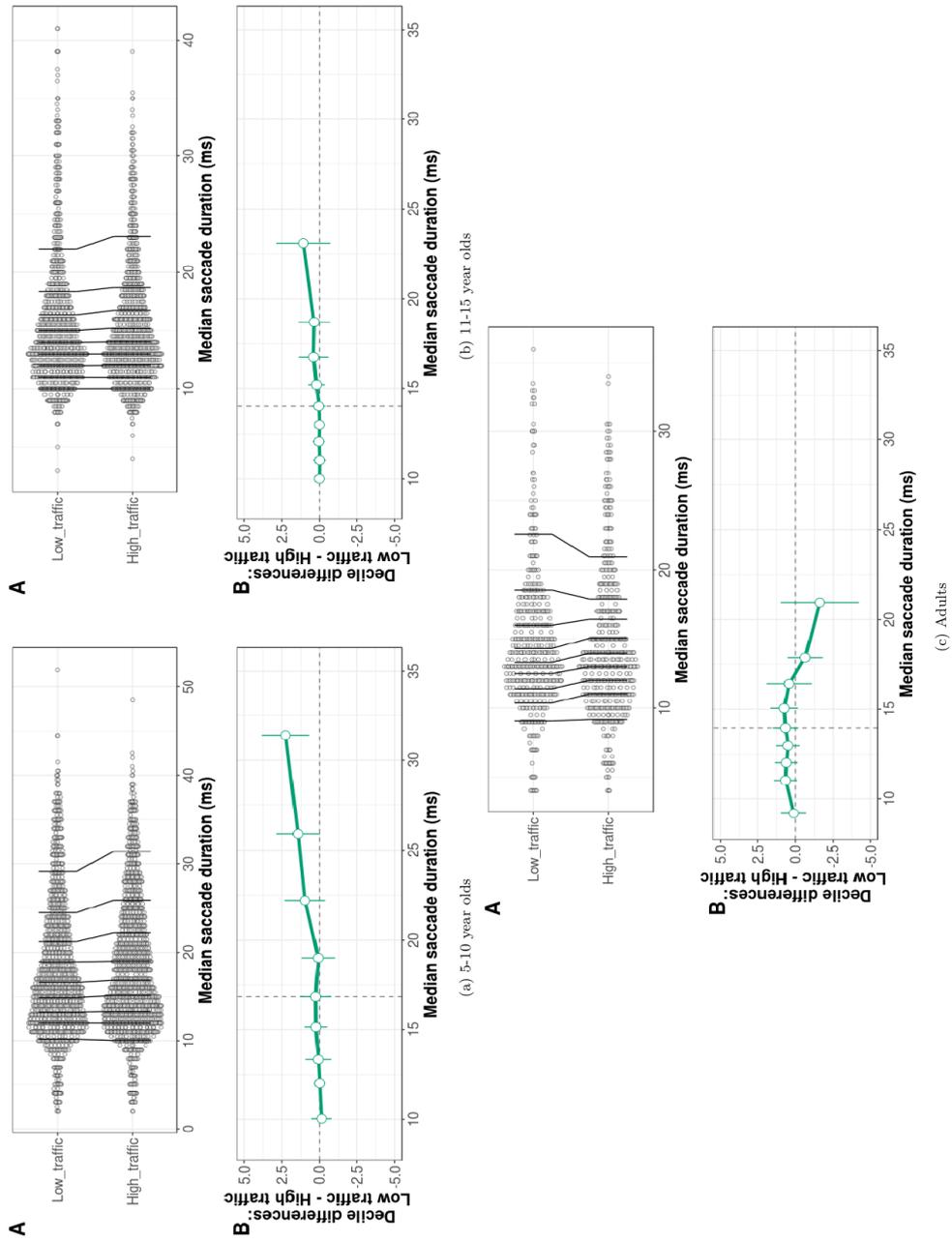


Figure A.16: **Shift functions for the median saccade duration for traffic density** (a) shows the difference in the median saccade duration for 5-10y/os, (b) for 11-15y/os, and (c) for adults on trials with low and high traffic density.

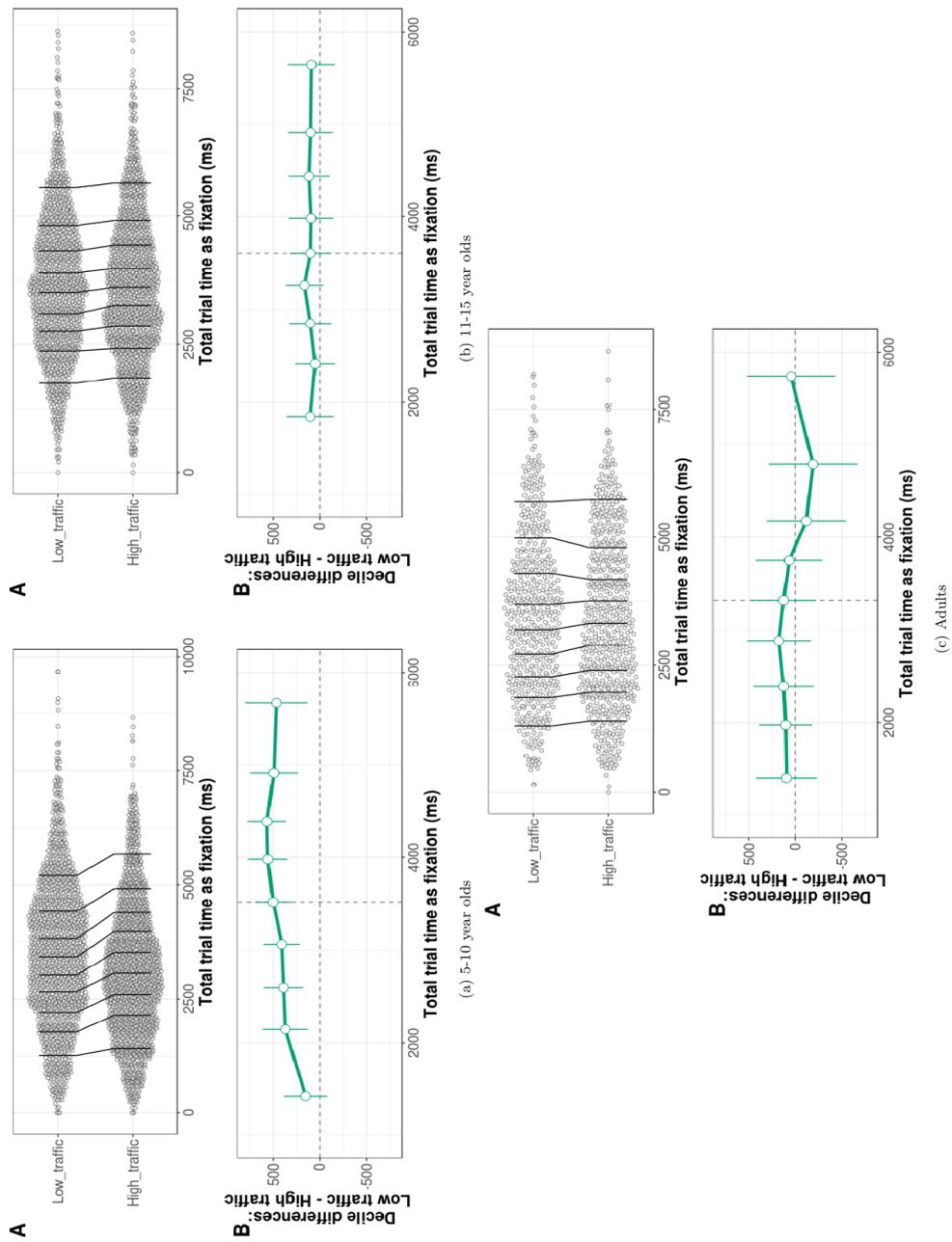


Figure A.17: **Shift functions for the proportion of trial time as fixation with traffic density** (a) shows the difference in the proportion of trial time as fixation for 5-10y/os, (b) for 11-15y/os, and (c) for adults on trials with low and high traffic density.

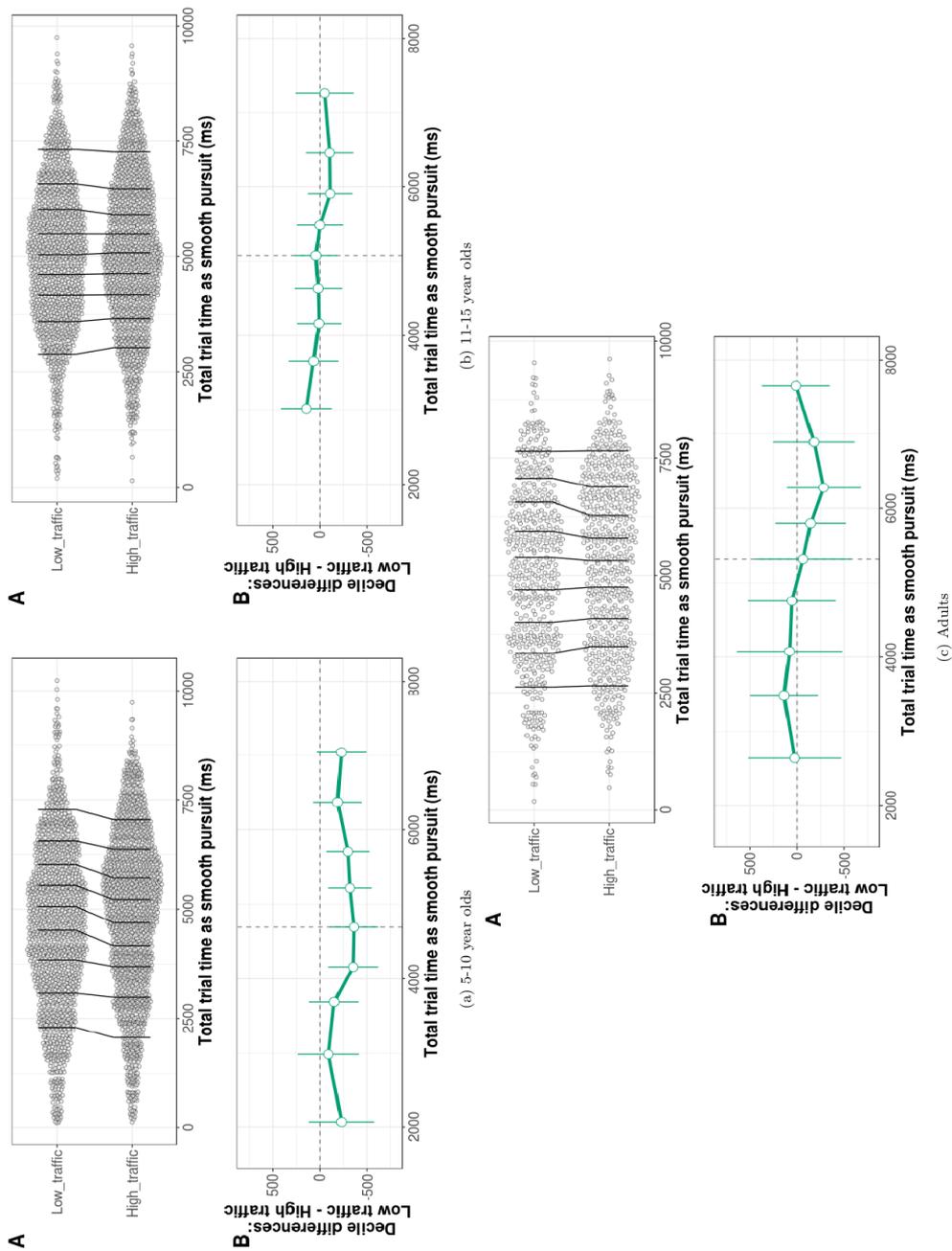


Figure A.18: Shift functions for the proportion of trial time as smooth pursuit with traffic density (a) shows the difference in the proportion of trial time as smooth pursuit for 5-10y/os, (b) for 11-15y/os, and (c) for adults on trials with low and high traffic density.

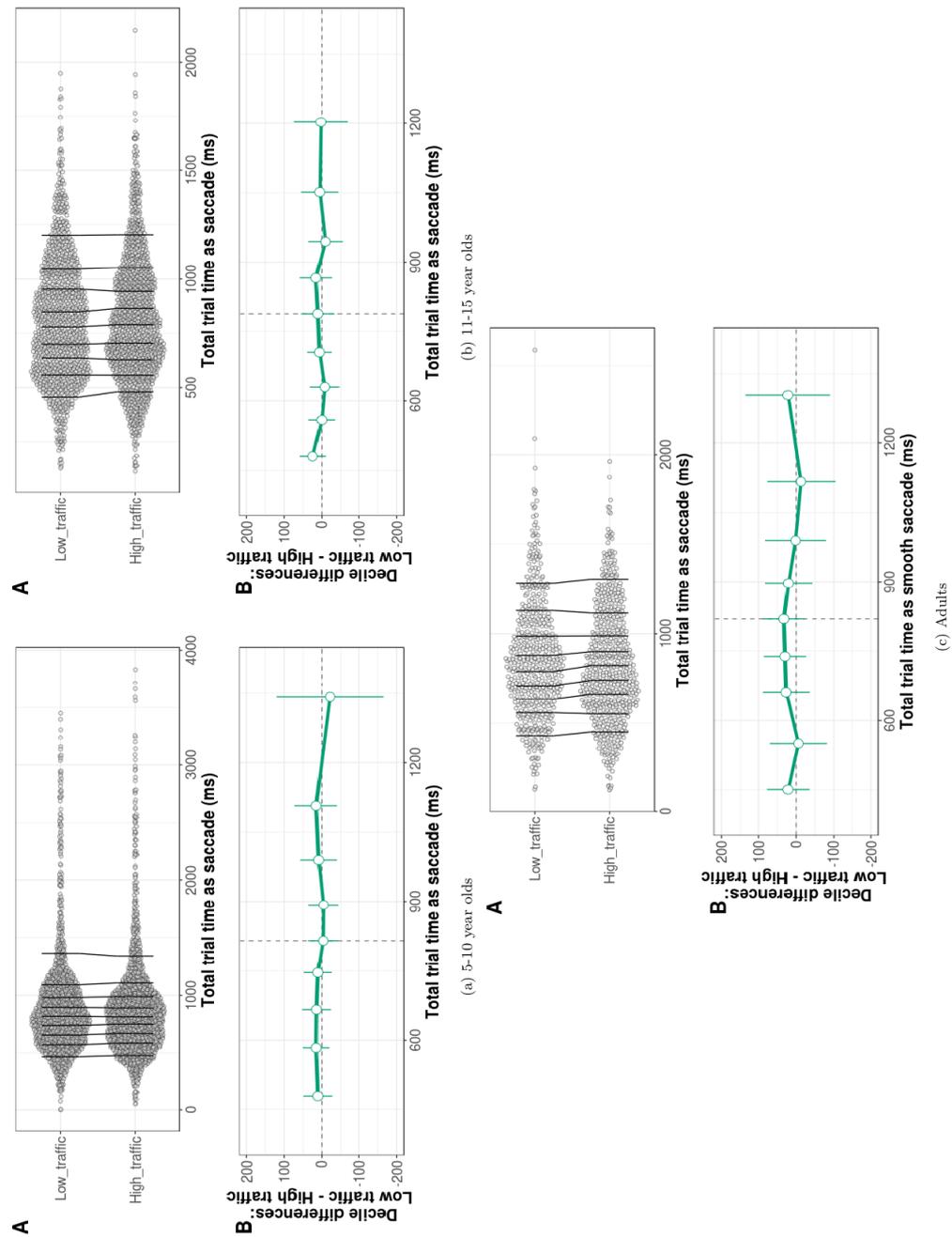


Figure A.19: **Shift functions for the proportion of trial time as saccades with traffic density** (a) shows the difference in the proportion of trial time as saccade for 5-10y/os, (b) for 11-15y/os, and (c) for adults on trials with low and high traffic density.

## A.2 Supplementary Results

### S20. Summary of the shift function analysis

5-10y/os made significantly more fixations (complete shift) when human distractors were present in the trial (Figure A.2). On the majority of trials where pedestrians

were present 11-15y/os made significantly more fixations. This effect was driven by trials where there were few, and trials where there were many fixations as deciles in the centre of the distribution were not significantly different from each other; though the median did show a significant difference – decile 5 (Figure A.2).

11-15y/os and adults made significantly fewer pursuits when human distractors were present – although the difference decreased in amplitude on trials with larger number of pursuits to a point where trials with the largest number of pursuits did not show a significant difference (Figure A.3b,c).

11-15y/os and adults had a significantly larger proportion of trial time as fixation (complete shift) when pedestrians were present (Figure A.8b,c). For 5-10y/os, trials which had a medium and large proportion of trial time as fixation were significantly affected by pedestrian presence. On trials where the proportion of trial time as fixation was small there was no significant effect of pedestrian presence (Fig. A.8a).

11-15y/os and adults had a significantly smaller proportion of trial time as pursuit gaze samples (complete shift) when pedestrians were present (Figure A.9b,c).

5-10y/os made significantly fewer pursuits when traffic density was low, however, for trials with a small number of pursuits the effect of traffic density was not significant (Figure A.12).

No other consistent effects were found. In sum, all age groups showed an impact of pedestrians on some of their global oculomotor characteristics while only 5-10y/os showed an impact of traffic density.

## A.3 Amendments and response to examiners for Chapter 2

### Responses to External Examiner

The description of the video clips, and of the task, is not detailed enough. Were the clips staged or natural? Was the camera always fixed and in the same location? How many clips had pedestrians? Were they edited to control anything about when cars emerged? Some justification for all of this would be good. There is also a mention of average car velocity, was that measured in the real world or estimated from the video? How?

The video clips were real (not staged) videos of a road crossing in Fribourg, Switzerland. The camera was always fixed in the same location seen in Figure 2.1a. Thirty-five of the videos contained pedestrians. The videos were not edited to control when the cars appeared in the video. The cars could appear at any point during the videos. The video clips were not edited or staged to maintain the highest amount of realism possible to try to get an idea of how participants would respond at a real road crossing. The camera position was maintained to make sure that the only aspects of the videos that changed was the traffic on the road and the appearance of pedestrians, but nothing in the background. 50km/h was the speed limit of the road and the average car velocity was based on the assumption that the majority of cars followed the speed limit of the road. This assumption was confirmed in Chapter 3 when I determined the speed of the vehicles using the automatic car detection algorithm. The Experimental Design subsection of the Methods section for Chapter 2 should be updated to the following to make these comments and the internal examiner's comments:

“At the beginning of the experiment participants were informed that they would be presented with a series of videos of road crossing situations on screen and that they would have to indicate by pressing the spacebar on a keyboard when they could cross the road and hold the button pressed for as long as they thought it was safe to cross. Participants were instructed to focus on approaching vehicles on the side

of the road closest to them but vehicles did travel on both sides of the road (see Figure 1.1a for a capture of the scene). Vehicles travelled at an average velocity of 50 km/h. Each trial started with the presentation of a central fixation cross. Once the participants had fixated on the cross a blank screen was presented for 500 ms and then the video clip for the trial was presented (see Figure 1.1a). Each trial was followed by another blank screen for 500 ms and the next trial started with the central cross. 100 trials were presented to the participants each with a different video clip, each lasting 10 seconds. All video clips were filmed at a real road crossing in Fribourg with a variety of traffic densities, with or without pedestrians and cyclists (distractors). The videos were completely natural and no aspects of the videos were staged and were not edited to control when the cars emerged. Thirty-five of the videos contained pedestrians. The camera was always fixed in the same location, at a height in between the average adult and the average child's height. Number of presses for each trial were collected and analysed for the purpose of the present experiment.”

**Regarding the task, it could be argued that pedestrians are highly relevant and not really distractors.**

Faces and biological motion have been shown to attract attention (Cerf, Frady, & Koch, 2009; Williams, Cristino, & Cross, 2019). Therefore, participants' attention was likely drawn to pedestrians irrelevant of whether they wanted to attend to them. If participants are attending to the pedestrians they are unable to take in the necessary information to make a safe crossing decision, so pedestrians are distracting from the task at hand.

**It is also not really explained why multiple button presses indicates poor performance (were they told to only cross once? What if there were many good opportunities?)”**

If children had faster locomotion speeds than younger adults they might be able to cross safely in smaller gaps than younger adults. However, children and younger adults have similar crossing speeds (O'Neal et al., 2017; te Velde et al., 2005).

Therefore, if children are crossing more often and in tight spaces that younger adults consider to be unsafe, children are showing risky crossing behaviour.

As younger adults are involved in the fewest road crossing accidents (World Health Organization, 2013, 2015), I assume they have the optimal road crossing strategy. Therefore, if young children are choosing to cross more often than younger adults they are likely to be choosing to cross at a point when younger adults consider it to be unsafe to cross. This would make crossing more often riskier crossing behaviour.

**Is the EyeLink velocity threshold 50 deg/s? I thought it was 30 by default, though it might depend on the model and settings. And it uses acceleration thresholds too, I believe.**

You are correct that the EyeLink velocity threshold is 30 and not 50. The most accurate would be to say that I set the velocity threshold manually starting with a threshold at 30°/s to match the EyeLink Manual, increasing to a maximum of 80°/s, if the first threshold was too low for a given participant. I changed the velocities manually at an individual level to adapt to the differing levels of noise present in different participants. Noise which might be caused by factors related to the stability of the participant's eye which vary with age and any medication used. As well as noise that can be caused by factors related to the stability of the recorded eye movement signal such as dryness of the eye, makeup, occlusion due to the eyelid, reflections from glasses, etc. The Eyelink setting is acceptable on average but can sometimes lead to misrepresentations at an individual level which can bias the sample distribution.

The EyeLink velocity threshold reported in Chapter 2 should be changed to the following:

“The velocity threshold was set manually starting with a threshold at 30°/s to match the EyeLink Manual, increasing to a maximum of 80°/s, if the first threshold was too low for a given participant. I changed the velocities manually at an individual level to adapt to the differing levels of noise present in different participants.

Noise which might be caused by factors related to the stability of the participant's eye which vary with age and any medication used. As well as noise that can be caused by factors related to the stability of the recorded eye movement signal such as dryness of the eye, makeup, occlusion due to the eyelid, reflections from glasses, etc. The Eyelink setting is acceptable on average but can sometimes lead to misrepresentations at an individual level which can bias the sample distribution.”

**In general the custom eye movement detection here should be justified – if other papers don't do this, why should they and why was it important in your case?**

I used a custom algorithm mainly to be able to separate smooth pursuit eye movements from fixations. Smooth pursuits are difficult to separate from fixations as their velocity ranges overlap, making a solely velocity based classifier difficult to create (Komogortsev & Karpov, 2013). Moreover, eye tracking noise further blurs the quantitative boundaries between fixations and pursuits (Komogortsev & Karpov, 2013). Studies examining properties of smooth pursuit eye movements have typically calculated smooth pursuit gain, which is the ratio between eye velocity and target velocity (e.g. Maruta et al., 2010; Stubbs et al., 2018). This requires knowledge of the target velocity and in realistic videos, the target changes and it requires sophisticated image analysis to determine the velocity of cars from videos. Other techniques for parsing smooth pursuit eye movements from fixations and saccades which do not require knowledge of the target have been developed. These are based on dual velocity thresholds, velocity and dispersion, and principal component analysis, with and without binocular eye tracking have been developed (Komogortsev & Karpov, 2013; Larsson et al., 2015, 2016). The algorithm combining velocity, dispersion, and information works very effectively for moving dot and image stimuli but they did not work very effectively for realistic videos (Larsson et al., 2016). Another approach using machine learning was also shown to be effective on moving dot stimuli (Vidal et al., 2012), however, it has not been tested on realistic video stimuli and it requires the development of a training set. To my knowledge there

is no algorithm that separates out smooth pursuits from fixations effectively for realistic video stimuli, therefore, I decided to create my own. The advantages of this algorithm are that it effectively labels saccades, fixations, and smooth pursuits from data recorded when participants gazed at a realistic stimuli, without knowing the velocity of the cars, and only needing monocular tracking data.

The following should be added to the statistical analysis subsection of the methods section of Chapter 2 to help justify the decisions made:

“We used a custom algorithm to separate smooth pursuit and fixation eye movements. Previous Studies examining properties of smooth pursuit eye movements have typically calculated smooth pursuit gain, which is the ratio between eye velocity and target velocity (e.g. Maruta et al., 2010; Stubbs et al., 2018). This requires knowledge of the target velocity and in realistic videos, the target changes and it requires sophisticated image analysis to determine the velocity of cars from videos. Other techniques for parsing smooth pursuit eye movements from fixations and saccades which do not require knowledge of the target have been developed. These are based on dual velocity thresholds, velocity and dispersion, and principal component analysis, with and without binocular eye tracking have been developed (Komogortsev & Karpov, 2013; Larsson et al., 2015, 2016). The algorithm combining velocity, dispersion, and information works very effectively for moving dot and image stimuli but they did not work very effectively for realistic videos (Larsson et al., 2016). Another approach using machine learning was also shown to be effective on moving dot stimuli (Vidal et al., 2012), however, it has not been tested on realistic video stimuli and it requires the development of a training set. To our knowledge there is no algorithm that separates out smooth pursuits from fixations effectively for realistic video stimuli, therefore, we decided to create our own. The advantages of this algorithm are that it effectively labels saccades, fixations, and smooth pursuits from data recorded when participants gazed at a realistic stimuli, without knowing the velocity of the cars, and only needing monocular tracking data.”

**Was the process for detecting moving vehicles checked with manual annotation? Was it able to distinguish pedestrians/cars/cyclists/birds?**

The automatic car detection was checked against manual annotation. The automatic car detection only picked up vehicles and not cyclists, pedestrians, or birds.

**Was traffic density defined as the number of specific cars in a clip? Or the number of cars per frame? Or some other way? I'm wondering about the difference between a clip with a single slow moving car vs. one with a single fast moving car. Are they both equally "dense"?**

Traffic density is defined as the average number of vehicles that occupy 1 mile or 1 kilometre of road space, expressed in vehicles per mile or per kilometre (McGraw, 2003). Therefore, the traffic density is the same whether a car travels quickly or slowly. For the videos clips I decided the closest match to the definition of traffic density would be the number of cars per video clip.

**If a car disappears behind an occluder and reappears, does the toolbox recognise this as two cars?**

A Kalman filter was used to maintain the track of an object when it disappears behind an occluder, therefore, a car that disappeared behind an occluder and reappeared was counted as one car.

**I think it would be difficult for anyone who didn't know about iMap to work out what was being done here or what the aim was.**

The aim in using iMap was to determine where participants looked during the videos, how this changes depending on changes in the scene such as the presence of pedestrians or changes in traffic density, and how this changes across the lifespan. This can be done using heatmaps of the gaze positions or area of interest (AOI) analysis but heatmaps are descriptive while iMap produces statistical gaze maps. AOIs would require previous knowledge of where participants are likely to look during a road crossing. From previous research (Tapiro et al., 2014) I can assume that children

would look at the appearing point of the cars and at the vehicles but participants may also look elsewhere, which would be missed by using AOIs. Moreover, AOIs rely on a-priori subjective segmentation of the stimulus space (Caldara & Miellet, 2011). This subjective segmentation can lead to problems such as engendering natural variations across authors, which in some cases lead to difficulty in generalizing observations across studies (Caldara & Miellet, 2011). AOIs are also in danger of circular analysis and “double-dipping” – the use of the same dataset for selection and selective analysis (Caldara & Miellet, 2011; Kriegeskorte et al., 2009).

**In theory, this could be done separately for each video frame or for a particular time window, and it is never explicitly stated that data is pooled across the entire video. The one sentence explanation says that maps were computed from “gaze positions”. So is that just fixations? Or also pursuit and saccades?**

Fixation, and smooth pursuit gaze positions were pooled together to compute statistical gaze maps. The gaze maps pool the gaze positions across the entire video duration. I chose not to run iMap for every video frame or time window as I wanted to determine the baseline average gaze pattern for each age group in the different situations (pedestrian presence, traffic density) for each video and the differences between them. Moreover, iMap for every video frame and participant would be millions of data points to analyse which would be challenging in terms of computational power and would require the development of novel solutions to address temporal correlations. Although, eye tracking studies using road crossing stimuli have been done with children, younger, and older adults the studies have primarily used area of interest analysis (Tapiro et al., 2014). Therefore, no statistically significant baseline gaze pattern for all age groups has been established, so before entering more granular investigations, it was critical to provide a better understanding of the processes in play at a general level.

Once this baseline had been established I could then investigate in more detail the time course of the gaze patterns in a follow up study but I felt this was beyond

the scope of the studies in Chapter 2 and Chapter 3.

The paragraph beginning “Statistical maps were calculated with the iMap toolbox, version 4” in the statistical analysis subsection of the methods for Chapter 2 should be altered to the following to account for the comments: “Statistical maps were calculated with the iMap toolbox, version 4 (Lao et al., 2017). iMap computes pixel-wise linear mixed models (LMMs) across participants and trials on each z-score gaze map which is pooled across the entire video. The z-score gaze map is created by pooling together fixation, and smooth pursuit gaze positions. The gaze maps pool the gaze positions across the entire video duration. The gaze maps are then z-scored. After the pixel-wise LMM is computed iMap uses a universal bootstrap clustering test to resolve biases in parameter estimation and problems arising from multiple comparisons (Pernet et al., 2011, 2015). This allows us to statistically isolate where and for how long eye movements are deployed to different points in the videos. ”

**I spent a while trying to compare the results in Table 2.1 and the appendices. The thing that jumps out from the table is that both the number of fixations and the number of pursuits increases with age, but this is not mentioned in the core text and I’m not sure it is ever tested**

This is correct and the following table should be added to the chapter and the results text under eye movement results should be updated to:

“ There was a significant increase in the number of fixations, and smooth pursuits with age (See TableA.1). All other general oculomotor characteristics were within a similar range for each age group (see Table 2.1). Critically, all age groups showed an impact of pedestrians on their global oculomotor characteristics, while only 5–10 y/os showed an impact of traffic density. There was an overall trend for the number of fixations for 5–10 and 11–15 y/os to increase when pedestrians were present in the scene. Adults and 11–15 y/os showed an overall trend to decrease their number of pursuits. All groups showed an overall trend of increasing trial time as fixation when pedestrians were present. Additionally, 11–15 y/os and adults showed an

overall trend of decreasing total trial time as pursuit when pedestrians were present. Finally, 5–10 y/os showed an overall trend of decreasing the number of pursuits with lower traffic density. Supplementary Figures S2–S19 and summary S20 provide a detailed description of subtle differences in the distributions at the decile level.

Table A.1: Differences in the number of fixations, pursuits, and saccades. Differences between means are indicated followed by 95% confidence intervals in the square brackets, and then p-values.”

<i>Global characteristics</i>	<i>5-10yr vs 11-15yr old</i>	<i>5-10yr old vs Adults</i>	<i>11-15yr old vs Adults</i>
<b><i>Fixations</i></b>			
Number of	-1.15 [-1.92,-1.01] p<0.001	-2.15 [-2.92,-1.91] p<0.001	-1.01 [-1.47,-0.57] p=0.004
<b><i>Smooth pursuits</i></b>			
Number of	-0.45 [-0.97,-0.02] p<0.001	-1.47 [-2.12,-1.04] p<0.001	-1.02 [-1.45,-0.97] p<0.001
<b><i>Saccades</i></b>			
Number of	5.15 [6.03,4.35] p<0.001	-8.00 [-8.98,-6.83] p<0.001	-2.85 [-3.84,-1.58] p<0.001

**The table says that it reports “proportion of trial time” but it actually reports absolute amount of time**

This would be more precise and the caption for Table 2.1 should be updated to: “Table 2.1: General oculomotor characteristics. The mean number of and total trial time as each eye movement type. Square brackets contain 95% confidence intervals.”

**The events listed don’t add up to 10s, and it looks like there is more “missing” time for the youngest age group. I also don’t really understand how the youngest group can have more saccades but fewer fixations and pursuits. Doesn’t a saccade always have to end in a fixation or a pursuit?**

The gaze data does not add up to 10s as some data was lost due to blinks or other track losses. The missing time is higher for younger children as they were more likely to move around causing track losses but also blinked more often than the other two age groups. Young children made more saccades but fewer fixations and smooth pursuits. This may be due to the children having more track losses and blinks, as children may have saccaded and then the track was lost or the child blinked.

**This would be easier to understand if (d) had an x axis label**

The x axis label for Figure 2.2d should be updated to Figure A.20 below. The x axis is trial number, however, the gaze maps were sorted by the correlation coefficient

and not by trial number, therefore the x axis label is not informative as it would be jumbled trial numbers.

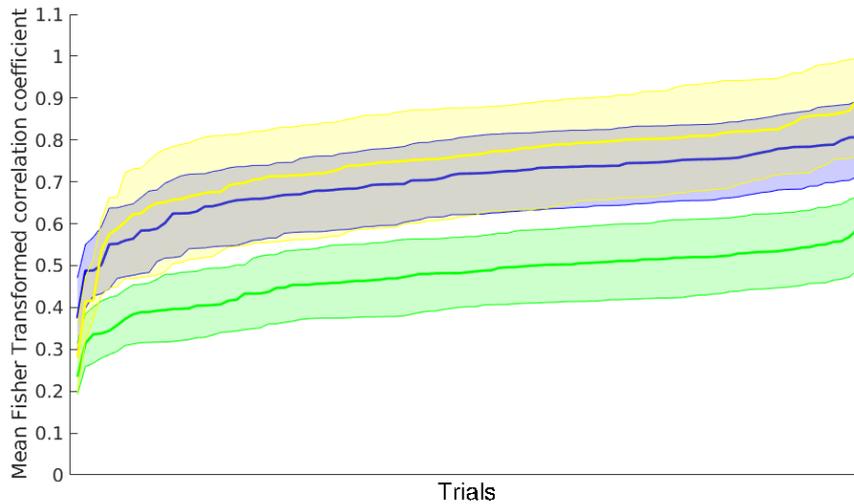


Figure A.20: The mean Fisher transformed correlation coefficient, with bootstrap confidence intervals for each trial, sorted by highest value. Data in yellow are from adults, blue from the 11–15 y/o group, and green from the 5–10 y/o group.

The text should be more precise about interpreting these numbers. It says that 5-10 y/os have the least “consistency in gaze behaviours” but more precise is that the spatial position of fixations (or eye position? See above) is less similar when pooled over the whole video. We don’t actually know from this data whether other aspects of gaze behaviour, such as pursuit time, or tendency to look in the same place at the same time, are more or less consistent

I agree this is imprecise and the sentence containing “Consistency in gaze behaviours” on page 31 should be changed to:

“Thus, GSMs reveal the variability or consistency in spatial gaze position (all eye movement types pooled across time) through the experiment (across trials)”.

**How should we interpret F/betas here? How was the scaling chosen? I can only see blue on the top row but I don't know if F=45 has a special meaning. Actually, I don't really understand where the black contours come from either, particularly in (g)-(i)**

In rows A, B, and D of Figure 2.3 the higher the numbers the more participants gaze in those locations for both beta coefficients and F values. The scales are determined by taking the maximum and minimum beta coefficient or F value across all the statistical gaze maps for a particular LMM result. In row C the images are linear contrasts between the age groups, (g) is the contrast between adults and 5-10 year olds, (h) the contrast between adults and 11-15 year olds, and (i) is the contrast between 11-15 years olds and adults. In all panels the warmer red colours indicate areas where the older age group looked more often during the video and the cooler blue colours indicate where the younger age group looked more often. The black line indicates clusters that show a significant contrast or significant difference between the groups. Therefore, although the difference may appear large, for example the bright red spot just below the appearing point in (i) it is not significant.

For (g) there is a blue cluster on the appearing point and slightly further down the road and a red cluster above and below this blue cluster at the appearing point. I would interpret this as children aged 5-10 years old looking significantly more at the centre of the appearing point and further down the road than adults did. Meanwhile, adults look more at the appearing point, both above and below the areas that 5-10 year olds look, but this difference was not significant as both clusters are not within the black lines. In (h) there is a red cluster on the appearing point and a blue cluster below the appearing point and further down the road. I would interpret this as adults look significantly more than 11-15 year olds at the appearing point. 11-15 year olds look below the appearing point and further down the road than adults but this difference was not significant as it is not within the black lines. For (i) there is a blue cluster on the appearing point which stretches further down the road. There is also a red cluster just below the appearing point. In this case 5-10 years olds look significantly more at the top of the appearing point and further down the road than

11-15 year olds. 11-15 year olds look more at the bottom of the appearing point than 5-10 year olds but this difference was not significant as the red cluster is not within the black lines.

In all panels the black contour indicates areas of the video where participants look significantly. Significance was determined using bootstrap clustering in the following way. For each pixel in the image an LMM is computed with pixel intensity (combined gaze frequency and duration) as the response variable for each pixel in the gaze map to produce a statistical gaze map (See Chapter 2 Methods for the LMM model I ran). IMap also computes the F and p values for each of the LMMs. The outputted statistical map is thresholded at  $p < 0.05$ . From the thresholded map iMap records the maximum cluster characteristic across all significant clusters in the statistic map. IMap then randomly shuffles the response variable and randomly draws with replacement new values for the response variable, the predictor variable, and the error. Another LMM is calculated and again the resulting statistic maps are thresholded and the maximum cluster characteristics are recorded. This process is repeated a large number of times to get the cluster characteristic distribution under the null hypothesis. The original statistic map calculated by iMap is then thresholded at  $p < 0.05$  and iMap compares the selected cluster characteristic with the value of the null distribution corresponding to the 95th percentile. Any cluster with the chosen cluster characteristic larger than this threshold is considered significant.

The above paragraph should be added to the statistical analysis subsection in the methods section of Chapter 2 to account for the examiner's comment.

**How was the background here selected? Some might see this as a bit misleading because the scene is going to change over time, and thus we don't know whether a particular spot is being looked at when it is empty (as in the figures) or when it is occupied by a car or pedestrian**

The background image is an average of all the videos used in the experiment. This average image is used for all the panels in this figure. I did not choose a particular time frame as the gaze maps represent the overall viewing densities across time and

trials. Therefore, the most fitting representation I could think of was to present the data on the average frame rather than a particular time point. However, these representations could have been improved by taking the average image of the video frames only showing pedestrians when the impact of pedestrian distractors is presented in the results, or an average of videos where traffic density is high for showing the impact of high traffic density.

The following sentence should be added to the caption for Figure 2.3 to account for the examiner's comment:

"The background image is an average of all the videos used in the experiment. This average image is used for all the panels in this figure."

**Why was a Yuen's test used and not a more conventional test? I thought that this was just an alternative to a t-test, but I'm confused by the large degrees of freedom which don't correspond to participant numbers. Elsewhere in the thesis you use LMM for this kind of comparison**

A Yuen's test was used as it performs well when using trimmed means, even with small sample sizes (Wilcox & Rousselet, 2018). Given the small sample size in the young adult group, I decided to go with the Yuen's test rather than a t-test. The Yuen's tests were bootstrapped giving unusual degrees of freedom, however, they should not have been reported at all as the bootstrap distribution does not assume an underlying distribution. In this experiment I compared this data using a bootstrapped Yuen's test instead of an LMM as done in later chapters. In this experiment I wanted to determine the difference in the number of crossing decisions across age and I did not look into the impact of pedestrian presence and traffic density on the number of crossing decisions. In later chapters I use an LMM as I looked at how the number of crossing decisions and time to impact were affected by age and other factors such as traffic density, or pedestrian presence. In the current chapter I did not look at the impact of additional factors as I wanted to develop an initial idea of participant's crossing behaviour and how this changes with age. From there I could build on this knowledge with more complex analyses once a baseline

had been determined.

Because of the issues I have highlighted, some of the statements in the discussion here should be more precise as they are currently not well supported by the data. 5-10y/os show “a much less systematic gaze scanpath”. This is actually about between participant variability, I think, but the term scanpath is usually used differently and it is not clear which analysis supports this statement. “Older children and adults mainly looked at the beginning of the vehicle’s trajectory”. Since the analysis doesn’t take into account where the cars are, how do we know this? “Only younger children showed direct gazing at the areas with pedestrian distractors”. I don’t see evidence for this. In Fig 2.3 d,e,f all of the age groups have a black contour which extends over the sidewalk. Maybe you need to highlight which region contained the pedestrians or specify what analysis this relates to. It seems unlikely that the other age groups NEVER looked there, which is what this statement implies

The statement that 5-10 y/os have a much less systematic scanpath is fully supported by the GSM data. The GSM analysis shows that the gaze patterns for 5-10 are less consistent across trials than for 11-15 or adults. Gaze maps may be different from scanpaths but different gaze maps always originate from different scanpaths. However for precision the sentence stating:

“5-10y/os show a much less systematic gaze scanpath” on page 35 should be changed to:

“GSM results indicate that 5-10y/os show much less systematic gaze patterns”.

The statement that older adults and children mainly looked at the beginning of the vehicles trajectory is supported by the iMap results. The iMap results for each age group shows that participants look at the top of the road where the roundabout is, as indicated by the colour contour lines in Figure 2.3d-f. Cars enter the road from the roundabout and begin their trajectories at the top of the road. This is the only location that cars can begin their trajectories from in the video. For clarification

the sentence stating:

“Older children and adults look mainly at the beginning of the vehicles trajectory” should be changed to:

“Older children and adults look mainly at the appearing point which is the beginning of the vehicle’s trajectory.”

The statement that only younger children showed direct gazing at areas with pedestrian distractors is also supported by the iMap results. Younger and older adults do gaze at the sidewalk significantly often across the whole experiment but not on trials where pedestrians are present. When pedestrians are present only young children significantly gaze at the sidewalk as shown in Figure 2.3j. For clarification the sentence stating:

“Only younger children showed direct gazing at the areas with pedestrian distractors”, should be changed to:

“iMap results (Figure 2.3j) showed that only younger children showed significant direct gazing at areas with pedestrians on videos where pedestrians were present.”.

**There is a discussion here about covert vs. overt attention to people. I didn’t find this very convincing and it needs more explanation. Why does covert attention to people increase fixations and reduce pursuit (all age groups)?**

The smooth pursuit eye movements come from overtly tracking pedestrians or vehicles. Participants gazed mostly at the appearing point and not much further down the road suggesting they are overtly fixating on the appearing point and possibly not overtly pursuing the pedestrians or vehicles down the road. Instead of overtly pursuing the pedestrians or vehicles the participants might be covertly attending the pedestrians or the vehicles while overtly fixating the appearing point. If they are fixating the appearing point and covertly attending the pedestrians or vehicles then the number of pursuits would be lower than if participants overtly pursued the pedestrians or vehicles.

The text is trying to argue that the age difference is because children are somehow “captured” by people in an automatic way, but is that only based on the (small) difference in spatial gaze distribution or is there some other evidence for this? If children are looking more at people, it could also be that they are more interested in people, or that because they are less skilled at the task they don’t realise that the people are not very helpful. There doesn’t seem to be much evidence for automaticity here

On videos where pedestrians were present only children significantly gaze at locations where pedestrians were present. Older children and adults did not significantly gaze at areas where pedestrians were present on videos where pedestrians were present. One reason for this could be that older children and adults inhibit attentional capture by the pedestrians more effectively than younger children. However, you are correct, from the data in Chapter 2 I cannot rule out that children may look at pedestrians because of top-down factors such as not having the knowledge to know that gazing at pedestrians is not informative of whether a potential crossing is safe or not. I have preliminary data from a follow up study showing that when children are directly asked where they should look during the task they select the appearing point. When asked if looking at pedestrians is useful for the task children say no pedestrians are not useful. This data suggests that children know that pedestrians are distracting and are likely not attending them intentionally.

Alternatively, children might be more interested in other pedestrians than older children and adults. Therefore, the following section of Chapter 2:

“The young children’s gaze patterns were characterised by less consistency across trials and more spread across the stimulus space. More specifically, younger children looked significantly more at the sidewalk area than adults and older children when human beings were present in the scene. This suggests that human beings attract the overt attention of younger children but not of older children and adults. Interestingly, human beings in the scene disrupted general oculomotor measures (more fixations, fewer pursuits, smaller proportion of trial as pursuit, and larger propor-

tion of trial as fixation) for all age groups. Hence, it seems that socially relevant stimuli (including faces, body motion, etc.) capture the covert attention of all age groups but that only younger children direct their gaze towards this type of stimuli, which are irrelevant to the crossing task. It is possible that older children and adults are able to inhibit saccades towards irrelevant stimuli, while younger children are lacking the inhibitory control to do so. This scenario is consistent with the findings of psychophysical and neuroscientific studies that children are less able to inhibit automatic saccades, instead directing their overt attention towards task irrelevant stimuli, which is linked in the literature to the ongoing maturation of executive functions due to a protracted maturation of frontal lobes (Munoz & Everling, 2004; Paus, 1989).”

Should be changed to:

“The young children’s gaze patterns were characterised by less consistency across trials and more spread across the stimulus space. More specifically, younger children looked significantly more at the sidewalk area than adults and older children when human beings were present in the scene. This suggests that human beings attract the overt attention of younger children but not of older children and adults. Interestingly, human beings in the scene disrupted general oculomotor measures (more fixations, fewer pursuits, smaller proportion of trial as pursuit, and larger proportion of trial as fixation) for all age groups. Hence, it seems that socially relevant stimuli (including faces, body motion, etc.) capture the covert attention of all age groups but that only younger children direct their gaze towards this type of stimuli, which are irrelevant to the crossing task. It is possible that older children and adults are able to inhibit saccades towards irrelevant stimuli, while younger children are lacking the inhibitory control to do so. This scenario is consistent with the findings of psychophysical and neuroscientific studies that children are less able to inhibit automatic saccades, instead directing their overt attention towards task irrelevant stimuli, which is linked in the literature to the ongoing maturation of executive functions due to a protracted maturation of frontal lobes (Munoz & Everling, 2004; Paus, 1989). However, it cannot be ruled out that younger children overtly attended

to pedestrians because they are more interested in people than older children and adults. Alternatively, as young children have less experience crossing roads than older children and adults they may not have realised that attending to pedestrians is not helpful to making a safe crossing decision”

### **A.3.1 Responses to internal examiner**

#### **When was this study conducted?**

The data collection was done in late 2015 to early 2016. The pre-processing and data analysis was done throughout 2016. The write up of the publication was done throughout 2017 and early 2018.

**One thought about the distractors: it occurs to me that children may perceive other pedestrians very differently from adults. Young children are quite vulnerable and may look longer at distractors to assess the potential threat they pose. That is, for younger children these pedestrians may not have been irrelevant for the road crossing task**

Children perceive less threat from stranger danger than adults (Esteban-Cornejo et al., 2016; E. Moran, Warden, Macleod, Mayes, & Gillies, 1997; Timperio, Crawford, Telford, & Salmon, 2004), and young children less so than adolescents (E. Moran et al., 1997). Therefore, it is unlikely that children perceive adult pedestrians as more of a threat than adolescents or adults in the task, and focus on other pedestrians to assess threat levels. Moreover, assessing the location of the other pedestrians is only important for when children are walking on the sidewalk, they do not provide any indication of whether it is safe to cross the road. Indeed, by attending to the pedestrians children would be unable to take in information about where the vehicles are on the road, preventing them from being able to make a safe crossing decision as they do not have the information required to do so. I also have some preliminary data from a follow up study that shows when children are asked whether looking at the pedestrians is useful, they answer with no pedestrians are not useful.

**How was the k-means clustering accomplished? Could people under 11 years old be placed in the same cluster as older kids? If not, how is this procedure any different from an a-prior t-test? Why weren't OAs included in this clustering?**

The k-means was performed using the Matlab k-means function. This separates a certain number of observations into a specified number of clusters in which each observation belongs to the cluster with the nearest mean. I inputted a 2-vector matrix of participant age and mean number of button presses the participants made as my observations, and my expected number of clusters as two. Two was the number different groups I expected to find based on the literature. It is theoretically possible for some 11 year olds to be places in the same cluster as 5-10 year olds but this did not happen in our case. Adults were not included in the clustering as the clustering was done to assess the existence of two separate groups of children in our data as had been seen in the literature.

**Was traffic only moving in one direction in the video? It does say they were supposed to focus on the lane closest to them but that doesn't preclude cars moving in the other lane. If there were such cars were they included in the traffic density LMM predictor?**

Traffic did move in both directions on the video. They were included as part of the traffic density calculation.

**I am guessing the videos were recorded from the height/viewpoint of an adult. How do you think this viewpoint may have impacted the decisions of much shorter children?**

The videos were filmed at a height at the midpoint between the average adult height and the average child height. This was done to reduce any impact on crossing behaviour and the information these age groups take in.

The experimental design part of the methods section for Chapter 2 should be updated to the following to account for these comments and the external examiner's

comments:

“At the beginning of the experiment participants were informed that they would be presented with a series of videos of road crossing situations on screen and that they would have to indicate by pressing the spacebar on a keyboard when they could cross the road and hold the button pressed for as long as they thought it was safe to cross. Participants were instructed to focus on approaching vehicles on the side of the road closest to them but vehicles did travel on both sides of the road (see Figure 1.1a for a capture of the scene). Vehicles travelled at an average velocity of 50 km/h. Each trial started with the presentation of a central fixation cross. Once the participants had fixated on the cross a blank screen was presented for 500 ms and then the video clip for the trial was presented (see Figure 1.1a). Each trial was followed by another blank screen for 500 ms and the next trial started with the central cross. 100 trials were presented to the participants each with a different video clip, each lasting 10 seconds. All video clips were filmed at a real road crossing in Fribourg with a variety of traffic densities, with or without pedestrians and cyclists (distractors). The videos were completely natural and no aspects of the videos were staged and were not edited to control when the cars emerged. Thirty-five of the videos contained pedestrians. The camera was always fixed in the same location, at a height in between the average adult and the average child’s height. Number of presses for each trial were collected and analysed for the purpose of the present experiment.”

**The difference in eye movement characteristics of time are obviously dependent on each other but also don’t add up to the same amount of time across participant group. This must be due to differences in excluded trials and samples correct?**

The gaze data does not add up to 10s as some data was lost due to blinks or other track losses. The missing time is higher for younger children as they were more likely to move around causing track losses but also blinked more often than the other two age groups.

**Were the differences in eye movement data predictive of differences in road crossing performance WITHIN each age group? That is, did the young kids who made crossing decisions similar to the older kids also display more similar eye movement behaviour to these older kids?**

I did not examine this as I felt it was beyond the scope of the study in Chapter 2. The main aims of the study were to determine the critical age at which children showed similar road crossing and attentional control abilities as adults and to determine whether differences in attentional control abilities across age was linked to their ability to make safe crossing decisions. The younger children that press as often as older children may have had similar eye movements to older children and this may be due to individual differences in the development of younger children. However, an additional study investigating individual differences in children's development and road crossing abilities may be more appropriate to examine this.

**Have you considered defining "safe crossing" periods and "unsafe crossing" periods within the video and assessing the proportion of time within these periods that participants are pressing the spacebar? Would such an analysis provide additional information or do you think it would just be retelling the same story?**

This is something that I considered. I decided to not include this analysis in the first study (Chapter 2) as it already contained multiple novel methodologies such as GSMS, my novel parsing algorithm, and automatic car detection. I needed to make sure I could carry out these analyses, along with iMap and shift function analyses, on eye tracking data recorded on videos by children and adults. I then had to put this together in a coherent paper that was not purely methodological. I, therefore, decided to keep more sophisticated analyses for future studies, after building more precise explanations based on the current findings.

**How do you think the use of shift functions compares to the use of Vincentile analysis or ex-gaussian distributional analysis?**

From my understanding Vincentile analysis is used in a descriptive manner similar to quantile plots. Shift functions have the added benefit of being able to provide statistical differences between each quantile of the distribution. However, assuming that one calculates the differences between Vincentiles similarly to the differences between quantiles (i.e. replace quantiles with Vincentiles in the shift function) in the shift function then one would likely obtain very similar results. Assuming you are referring to ex-Gaussian analyses in a similar way to that used by E. M. Palmer, Horowitz, Torralba, and Wolfe (2011), the data is fitted to an ex-Gaussian distribution and then the fit is analysed. The aim of which is to determine whether the data shows some of the mental processes associated with an ex-Gaussian distribution. By comparison the shift function directly compares the observed distributions to each other. Therefore, no inferences on what kinds of mental processes can be made based on the shape of the distribution but you do get a more direct comparison of the differences between the two group or sample distributions.

**Would the TTI analysis used in chapter 3 be informative for the data from chapter 2?**

The TTI analysis for Chapter 3 would be informative for the data in Chapter 2. I chose not to perform this analysis as I had not yet modified the automatic car detection algorithm to calculate TTI. I also wanted to have a simple measure of road crossing performance which would give me a baseline indication of crossing behaviour. I could then use this measure again in a follow up study, which I performed in Chapter 3 but in Chapter 3 I wanted to develop this measure further so I adapted the automatic car detection algorithm to calculate the TTI.

# Appendix B

## Supplementary materials for chapter 3

### B.1 Supplementary Figures

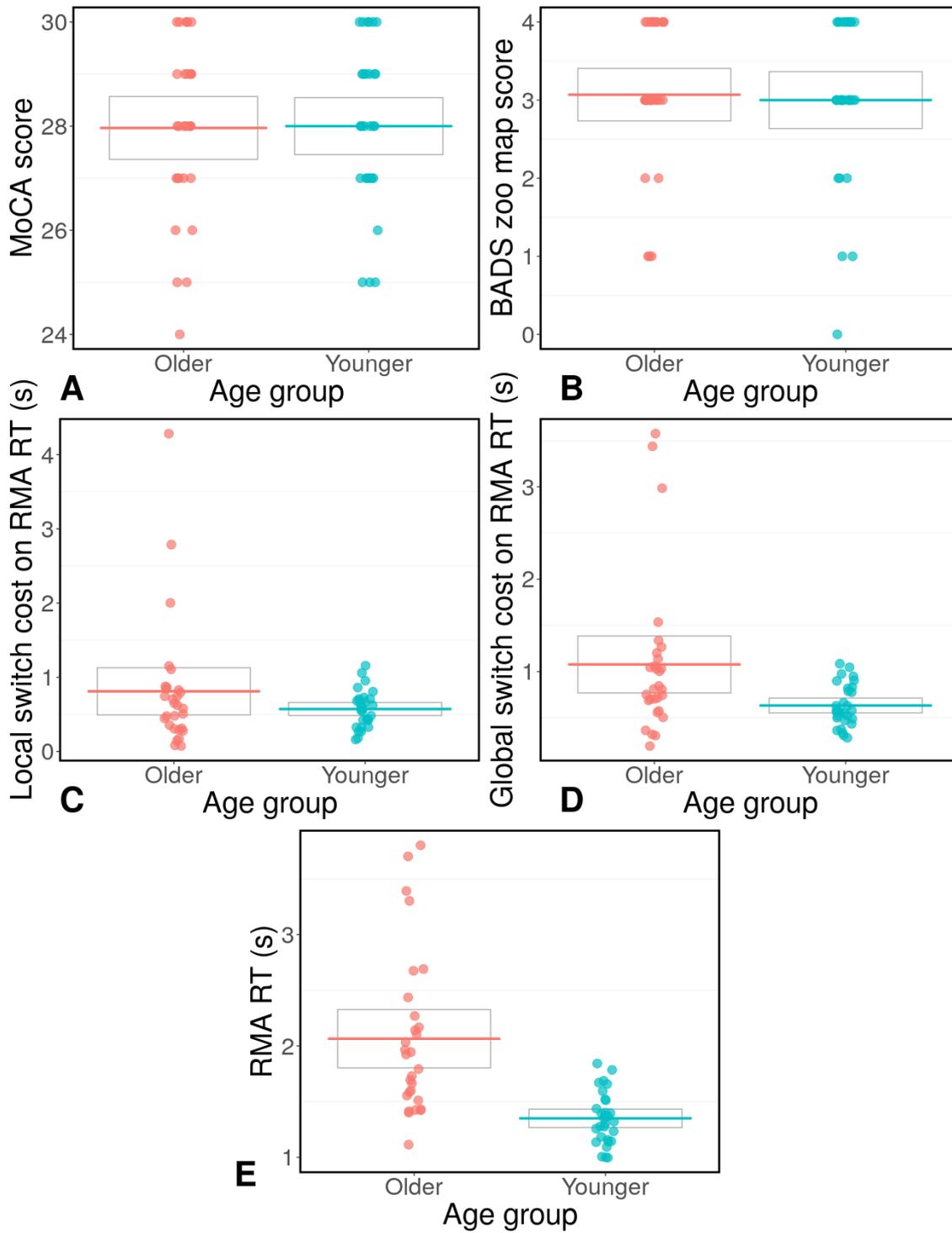


Figure B.1: Results for each executive function measure. (A) MoCA score. (B) BADS zoo map score. (C) Local switch cost on response time of RMA. (D) Global switch cost on response time of RMA. (E) Reaction times across all blocks of RMA. See Methods for how global and local switch costs were calculated.

## B.2 Supplementary Tables

Table B.1: Results from the linear mixed model on time to impact. Significant results are highlighted in blue. See Methods for the model that was run.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Age group	442.47	267.76	1.65	0.103
Traffic Density	20.07	54.45	0.37	0.713
Pedestrian presence	-189.93	158.44	-1.20	0.234
BADS zoo map score	-92.85	158.18	-0.59	0.565
Age group * traffic density	61.29	25.09	2.44	0.015
Age group * pedestrian presence	-64.33	67.28	-0.96	0.339

Table B.2: Results from the simple effects linear mixed model on time to impact for older adults. See Methods for the model that was run.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Traffic Density	102.13	77.15	1.32	0.191
Pedestrian presence	-332.07	58.86	-1.51	0.137
BADS zoo map score	52.30	219.15	0.24	0.813

Table B.3: Results from the simple effects linear mixed model on time to impact for younger adults. See Methods for the model that was run.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Traffic Density	11.88	52.10	0.23	0.820
Pedestrian presence	-140.95	82.53	-0.93	0.357
BADS zoo map score	-241.19	177.33	-1.36	0.185

Table B.4: Results from the linear mixed model on number of crossing decisions. See Methods for the model that was run.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Age group	-0.13	0.08	-1.68	0.096
Traffic Density	0.001	0.02	0.08	0.938
Pedestrian presence	0.04	0.05	0.01	0.463
BADS zoo map score	0.01	0.04	0.28	0.781
Age group * traffic density	-0.01	0.01	-1.13	0.259
Age group * pedestrian presence	-0.05	0.03	-1.60	0.110

Table B.5: Results from the simple effects linear mixed model on number of crossing decisions for older adults. See Methods for the model that was run.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Traffic Density	-0.02	0.02	-1.04	0.300
Pedestrian presence	0.006	0.05	0.12	0.907
BADS zoo map score	0.02	0.03	0.56	0.579

Table B.6: Results from the linear mixed model on the duration of button presses. See Methods for the model that was run.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Age group	-0.19	0.16	-1.25	0.215
Traffic Density	0.09	0.09	1.02	0.311
Pedestrian presence	-0.13	0.28	-0.46	0.648
BADS zoo map score	0.03	0.08	0.32	0.750
Age group * traffic density	-0.02	0.02	-0.76	0.446
Age group * pedestrian presence	0.04	0.06	0.71	0.477

Table B.7: Results from the simple effects linear mixed model on the duration of button presses for older adults. See Methods for the model that was run.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Traffic Density	0.07	0.09	0.77	0.444
Pedestrian presence	-0.15	0.30	-0.52	0.605
BADS zoo map score	-0.03	0.11	-0.26	0.800

Table B.8: Results from the simple effects linear mixed model on the duration of button presses for younger adults. See Methods for the model that was run.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Traffic Density	0.09	0.09	1.02	0.312
Pedestrian presence	-0.11	0.29	-0.39	0.699
BADS zoo map score	0.11	0.12	0.88	0.387

## B.3 Response to Examiners Comments

### B.3.1 Response to external examiners comments

**In general several of the comments from Chapter 2 apply here**

I have applied the same changes made in response to the comments from Chapter 2, to Chapter 3. I have updated the description of the video task to match that in Chapter 2. I have added more information about the eye parser algorithm and iMap, and how to interpret the iMap results.

**The F maps are not presented in the same way as in Chapter 2**

Figure 3.5A and B are presented in the same way as for Figure 2.3 row B. The higher the numbers the more participants gaze in those locations for both beta coefficients

and F values. The scale was determined by taking the maximum F value across all the statistical gaze maps for a particular LMM result. In all panels the black contour encircles areas of the video where participants look significantly. Figure 3.5 C is presented similarly to Figure 2.3 (j). However, instead of the interaction between age group and distractors it is the simple effect of distractors on older adults' gaze locations. I chose to present the simple effect rather than the interaction here as it is easier to interpret than the interaction. In Figure 3.5 D I wanted to highlight that distractors did not have a significant impact on gaze locations for younger adults, which is why the image shows no gaze data.

Moreover, the experiment in Chapter 3 was run two years after the experiment in Chapter 2. Visual representations produced with iMap, as is the case with SPM (fMRI), Fieldtrip (MEG) or EEGLab (EEG), might differ slightly between studies published several years apart. This is because these types of analyses are in constant development which allows them to be improved as soon as new statistical knowledge is produced.

**Importantly, although the method suggests that older adult and younger adult have a similar spatial distribution, because it ignores time it could be that the two groups look at cars/people at a different time**

As iMap pools the data over time older adults and younger adults could have looked at cars and people at different times. However, if younger adults looked at pedestrians as often as older adults, even at different times than older adults, then iMap would have shown a significant effect of distractors for younger adults. Our results do not show this therefore I can still conclude that younger adults do not look at distractors significantly often. In other words, as our conclusions are based on the differences in spatial gaze distributions, investigating the distributions at each time point should not change our conclusions compared to pooling gaze distributions across time. I have updated the text in the results and methods section of Chapter 3 to make it more explicit that the results show differences and similarities in spatial distributions but not over time.

## **Why was TTI investigated here but not in Chapter 2? This could be explained**

The experiment in Chapter 3 was performed two years after the experiment in Chapter 2. Based on the results in Chapter 2 I noticed a need for a finer grained measure of road crossing. Therefore, I had not yet modified the automatic car detection algorithm to calculate time to impact before the experiment in Chapter 3. In Chapter 2 I wanted to have a simple measure of road crossing performance which would give me a baseline indication of crossing behaviour. I could then use this measure again in a follow up study, which I performed in Chapter 3 but in Chapter 3 I wanted to develop this measure further so I adapted the automatic car detection algorithm to calculate the time to impact.

## **It says here that the maps used a 4deg kernel which is different from in Chapter 2, why?**

The gaze maps for older adults were noisier than for the participants in Chapter 2. I decided to increase the smoothing to reduce the impact of the noise. The choice of smoothing is a trade off between the spatial granularity of the analysis and robustness. Smoothing can reduce noise which helps to prevent false positives. This improves the robustness and statistical power of the analyses. However, too much smoothing would prevent the detection of subtle effects. As with neuroimaging techniques there is no standardised way to select the level or type of smoothing. This depends on scientific questions, preliminary results, expectations from literature, design, and the quality of the data. In Chapter 3, different age groups had different levels of noise in their oculomotor recordings, so I increased the smoothing to account for this. The question of the optimal smoothing is still debated in the literature (see Mikl et al., 2008) and is beyond the scope of this thesis.

### **B.3.2 Response to internal examiners comments**

**The number of abbreviations and their frequency of use is an undesirable feature of chapter 3**

The number of abbreviations in the text have been reduced such that the only remaining abbreviations in Chapter 3 are: EU, UK, ANOVA, MoCA, BADS, RMA, and y/o.

**In the BADS what happens if participants route in trial 1 meets the specified order required in trial 2?**

If the participant's route on trial 1 of the BADS test matches the order required in trial 2, they will receive full marks for trial 1. There is only one solution to the zoo map test and if participants perform the test correctly their order on trial 1 will match that of trial 2. There is a loop section in the correct route of the zoo map test which participants could go round in a different order on trial 1 compared to trial 2, however, this would not alter their score. I have altered the paragraph starting "To assess the participants' executive functioning abilities" in the executive function tests subsection of the Methods for Chapter 2 to the following:

"To assess the participants' executive function abilities, participants completed the BADS zoo map test (Wilson et al., 1996), and the Rogers and Monsell attention shift paradigm (RMA; Rogers & Monsell, 1995). The BADS zoo map test assessed the participants' spatial planning ability by assessing participants' ability to plan a route around a zoo. In the first trial participants were given a map of a zoo and instructed to plan a route around a zoo, starting at the entrance and finishing with a picnic. Along the route participants had to visit specified locations in any order while following set rules, such as only using specific paths twice and not visiting unspecified locations. Participants' planning time and time to complete the task was recorded. In the second trial participants had to plan a route around the same zoo, following the same rules, and visiting the same locations but in a specified order. Again, the participants' planning time and time to complete the task was recorded. Participants were scored based on visiting the correct locations and points

were deducted when participants broke the rules and exceed time limits for planning on the second trial. There was only one correct route on both trials, therefore, if participants do the task correctly their route for trial one will mostly match the route for trial two. The only exception being the order in which they go around a loop section of the map.”

### **How many interactions were included in the models?**

There were 2 interactions: age group \* pedestrian presence, age group \* traffic density. I have clarified this in the text by altering the paragraph starting “The crossing decisions were analysed using linear mixed models...” in the statistical analysis subsection of the Methods section of Chapter 3 to the following:

“The crossing decisions were analysed with linear mixed models with fixed effects of age group (above or below 60y/o), traffic density, distractors, and zoo map score. The model included two interactions one between age group and traffic density, and one between age group and distractors.”

### **What is the logic of removing all random effect slopes rather than following a pruning procedure such as that described in the parsimonious mixed model paper (Bates et al. 2015)**

I started with a maximal model as suggested by Barr et al. (2013), as this model did not converge I pruned the model by reducing the complexity of the random effects structure. I did not have a hypothesis of which fixed factor random slope was more important to take into account in the random effects structure, therefore I removed the slopes for all the factors.

Performing the pruning again using the pruning procedure suggested by (Bates et al., 2015) for the iMap model and the duration of button presses model, the most maximal model that converges is the model with all random slopes removed. For the model on the time to impact data and the number of crossing decisions was pruned to a model with only random slopes for the BADS zoo map test, as well as random intercepts for subject and item (video clip). The results remain the same but I have

updated the text in the statistical analysis subsection of the methods for Chapter 3, the numbers in the Results section and Tables B.1, and B.4 in Appendix B.

**I wonder again if older adults looking at distractors is impacted by their potential vulnerability. It may not be the case that other pedestrians are irrelevant to safe crossing decisions**

Assessing the location of the other pedestrians is only important for when older adults are walking on the sidewalk, they do not provide any indication of whether it is safe to cross the road. Indeed, by attending to the pedestrians older adults would be unable to take in information about where the vehicles are on the road, preventing them from being able to make a safe crossing decision as they do not have the information required to do so.

# Appendix C

## Supplementary materials for chapter 4

### C.1 Supplementary Figures

#### C.1.1 Relationship between TTI and DTI

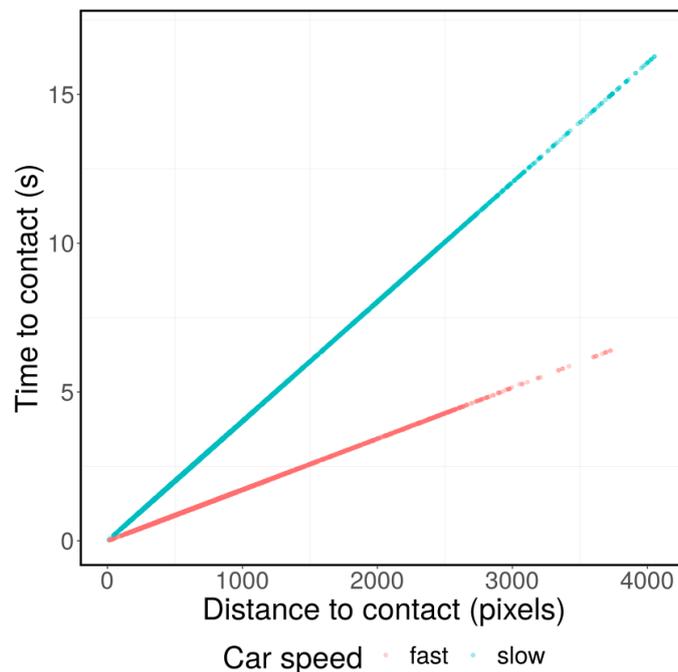


Figure C.1: The relationship between TTI and DTI when cars travelled quickly compared to slowly.

# Supplementary Figures for Experiment 1

## C.1.2 Main effects

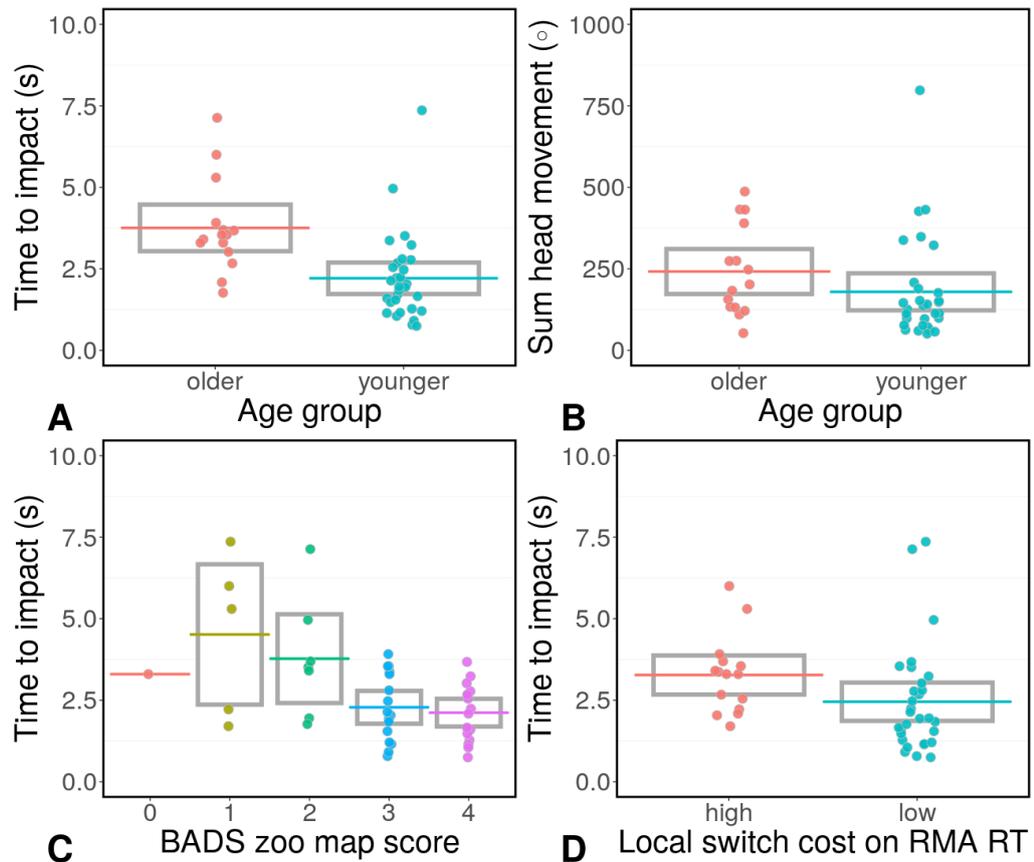


Figure C.2: Main effects of age group (A), BADS zoo map score (C), and local switch costs on the RMA task (D) on TTI. Main effect of age on amount of head movements participants made (B).

OAs had consistently longer TTI than YAs (Table C.27, Figure C.2A), and made shorter key presses than YAs (Table C.2, Figure C.4A). The LMM showed that OAs made more head movements than YAs (Table C.41, Figure C.2B). There was no difference between the number of crossing decisions made by OAs and YAs (Table C.1).

Participants with low BADS zoo map scores had longer TTI, and made shorter key presses than participants with higher scores (TTI: Table C.27, Figure C.2C; key presses: Table C.2, Figure C.4B).

Participants with larger local switch costs had longer TTIs than participants with smaller switch costs (Table C.27, Figure C.2D).

### C.1.3 Head Movements

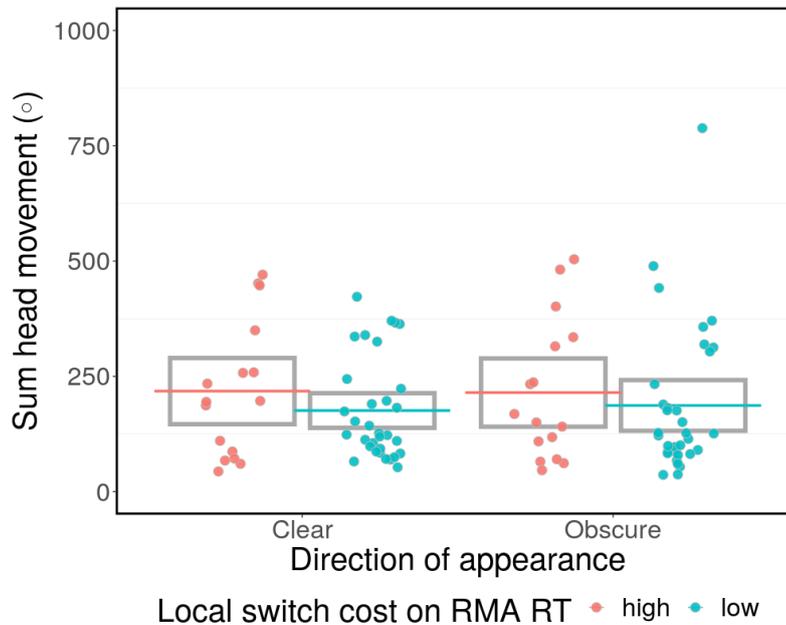


Figure C.3: The effect of travel direction on the number of head movements made by participants with small and participants with large local switch costs on the RMA task.

I analysed the head movements participants made by summing the change in angle of the head between each sample recorded on the trial. The LMM on head movements revealed a significant interaction between attention switching abilities, specifically local switch costs on the RMA task, and cars travelling from an obscured view, but this was not significant at each level of the local switch costs measure (Table C.41, C.43 and C.42; Figure C.3).

### C.1.4 Duration of key presses

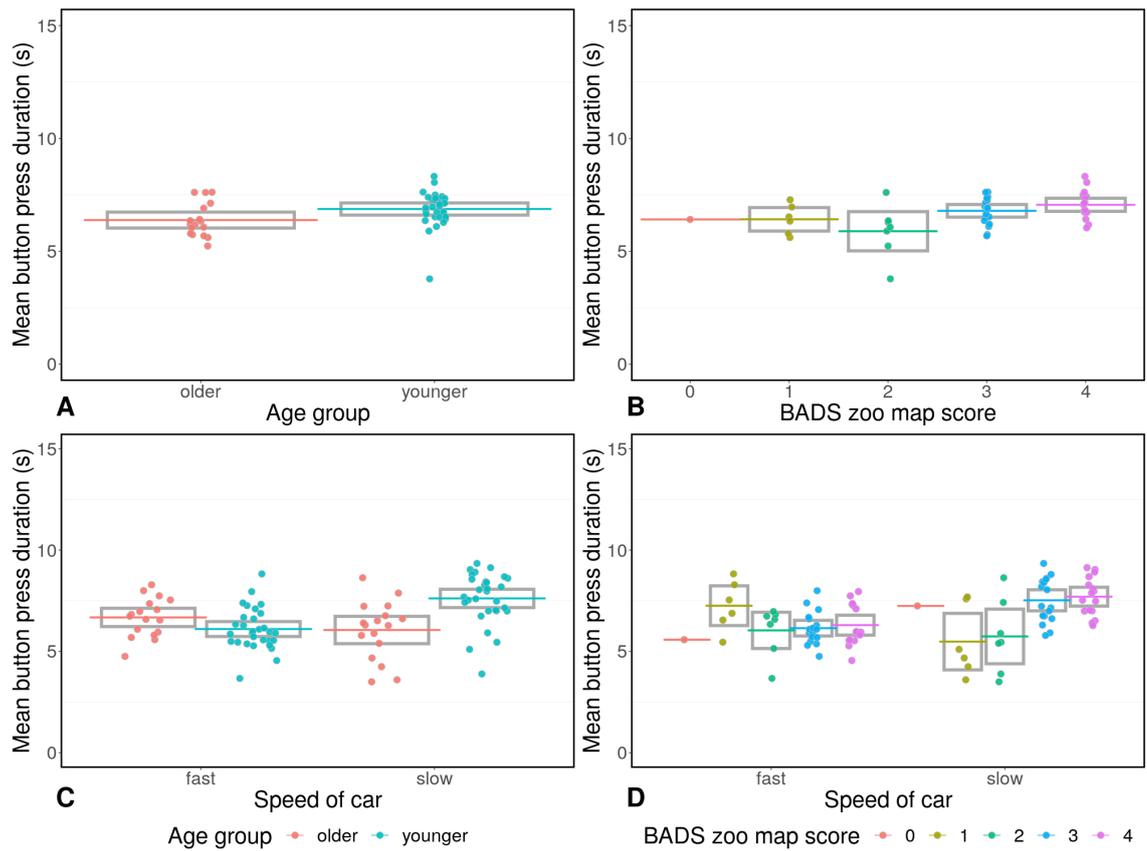


Figure C.4: Main effect of age group (A) and BADS zoo map score (B) on key press duration. Interaction between age group and car speed on key press duration (C). Interaction between BADS zoo map score and car speed on key press duration (D).

### C.1.5 RMA RT results

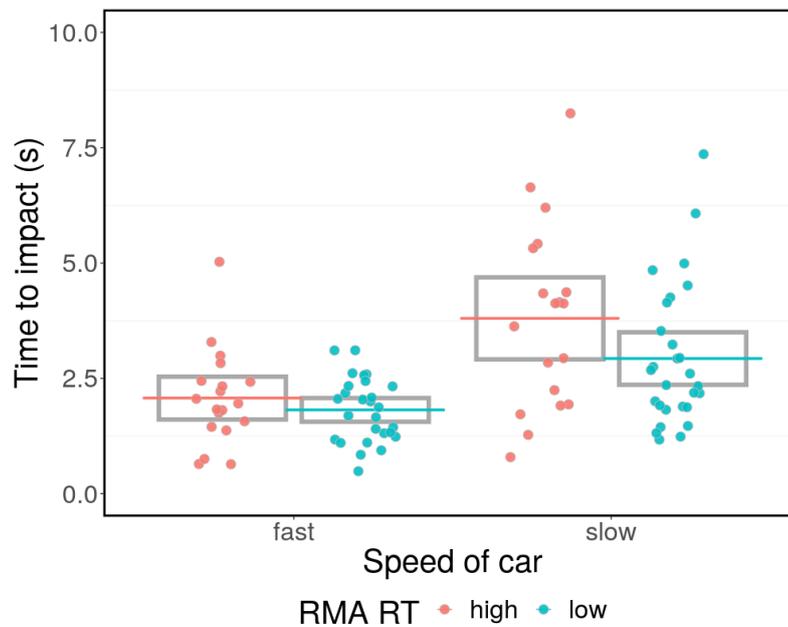


Figure C.5: Interaction between participants' RTs on the RMA task and car speed on TTI.

All participants reduced their TTI when cars travelled quickly compared to slowly (Table C.27). This reduction was greater for participants with slower RTs on the RMA task than participants with faster RTs (Tables C.33, and C.32, Figure C.5).

## Supplementary Figures for Experiment 2

### C.1.6 Main effects

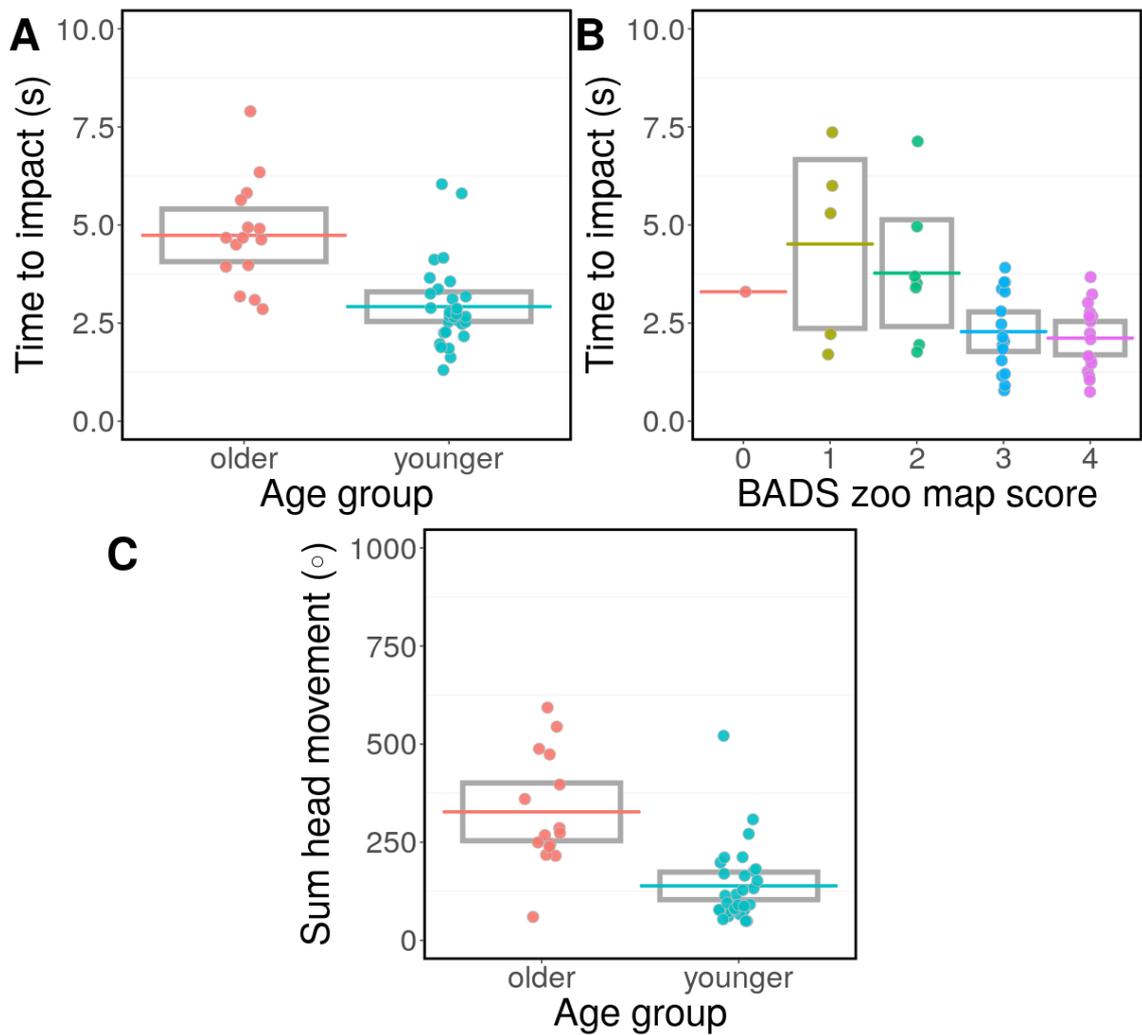


Figure C.6: Main effects of age group (A) and BADS zoo map score (B) on TTI. Main effect of age group on the amount of head movements participants made (C)

There were main effects of age on the duration of key presses, TTI, and amount of head movements participants made (Table C.18, C.34, and C.44). OAs made shorter key presses, had longer TTI, and made more head movements than YAs (Table C.20, C.19, C.36, C.35, C.46, and C.45; Figure C.8A, C.6A, and C.6C).

There were main effects of spatial planning ability on the TTI participants made (Table C.34). Participants with low BADS zoo map scores had shorter TTI than participants with high scores (Table C.40, and C.39; Figure C.6B).

### C.1.7 Head Movements

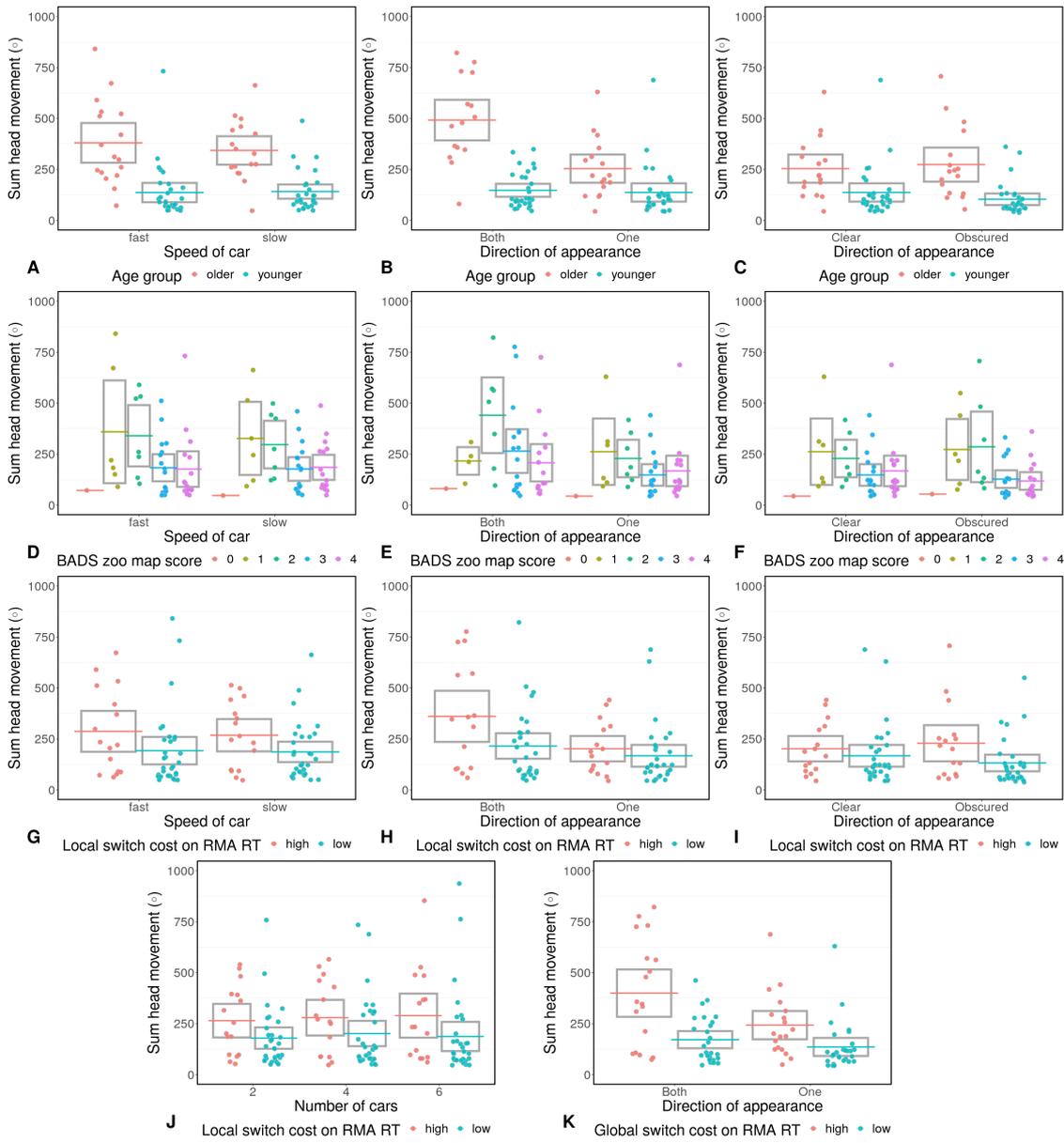


Figure C.7: The effect of car speed on the amount of head movements made by OAs and YAs (A), participants with high and low BADS zoo map scores (D), and participants with small and large local switch costs on the RMA task (G). The effect of cars coming from both directions on the amount of head movements made by OAs and YAS (B), participants with high and low BADS zoo map scores (E), and participants with small and large local and global switch costs on the RMA task (H,K). The effect of cars coming from an obscured viewpoint on the amount of head movements made by OAs and YAs (C), participants with high and low BADS zoo map scores (F), and participants with large and small local switch costs (I). The effect of traffic density on the amount of head movements made by participants with large and small local switch costs (J).

The LMMs on the amount of head movements participants made showed interactions between car speed and age group, and between car speed and spatial planning ability (Table C.44). OAs made more head movements, while YAs made

fewer head movements when cars travelled quickly compared to slowly (Tables C.46, and C.45; Figure C.7A). Participants with low BADS zoo map scores made more head movements when cars travelled quickly compared to slowly (Table C.49, Figure C.7D). Participants with high BADS zoo map scores did not significantly change their amount of head movements (Tables C.50, Figure C.7D). The LMM on the amount of head movements participants made also showed a significant interaction between car speed and local switch costs on the RMA task but the simple effects LMMs showed that this was not significant at each level of the local switch costs measure (Tables C.44, C.54, and C.53; Figure C.7G).

The LMMs showed main effects of travel direction on the amount of head movements participants made (Table C.44). All participants made more head movements when cars came from both directions compared to just one direction. The increase in amount head movements was greater for OAs than YAs, for participants with lower BADS zoo map scores, and for participants with larger switch costs (global and local) than participants with smaller switch costs on the RMA task (Tables C.45-C.54; Figures C.7B, E, H, and K).

The LMM on head movements showed a significant interaction between age group and travel direction, spatial planning ability and travel direction, and between attention switching ability and travel direction (Table C.44). Participants with low BADS zoo map scores made more head movements when cars travelled from an obscured view compared to a clear one (Table C.49, Figure C.7F). Participants with high BADS zoo map scores made fewer head movements when cars travelled from an obscured view compared to a clear one (Table C.50, Figure C.7F). The change in head movements was not significant for OAs or YAs, or participants with smaller or larger local switch costs on the RMA task (Table C.46, C.45, C.53, and C.54; Figures C.7C, and I).

The LMM on head movements showed an interaction between traffic density and local switch costs on the RMA task (Table C.44). Participants with small local switch costs made less head movements when traffic density was high compared to when it was low (Table C.53, Figure C.7J). Participants with large local switch costs

did not significantly differ in the amount of head movements they made when traffic density was high compared to when traffic density was low (Table C.54, Figure C.7J).

### C.1.8 Duration of key presses

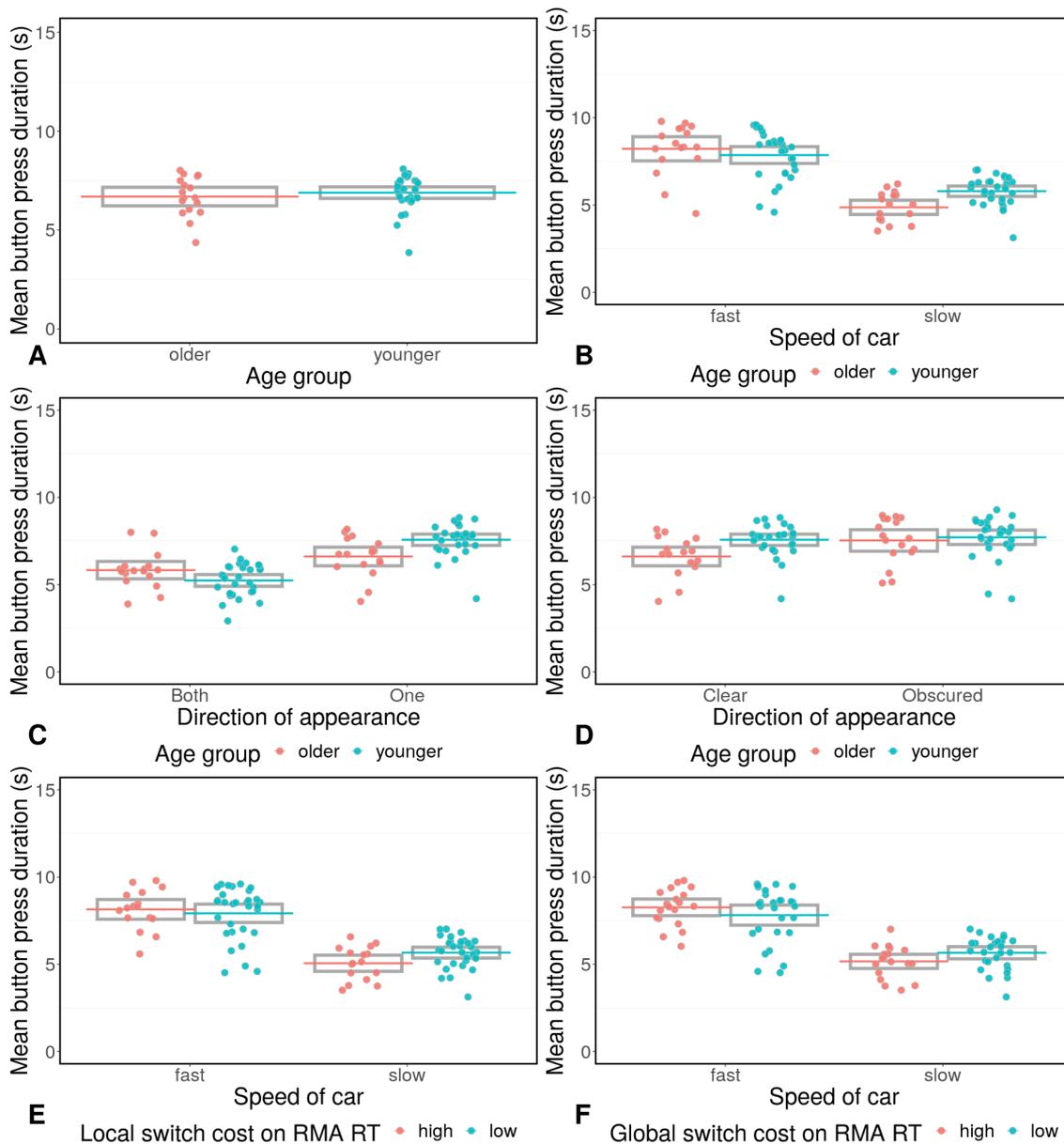


Figure C.8: Main effect of age group on key press duration (A). Interaction between age group and car speed on the duration of key presses (B). Interaction between age group and cars coming from both directions on the duration of key presses (C). Interaction between age group and cars coming from an obscured viewpoint on the duration of key presses (D). Interaction between local switch costs on the RMA task and car speed on the duration of key presses (E). Interaction between global switch costs on the RMA task and car speed on the duration of key presses (F).

### C.1.9 RMA RT results

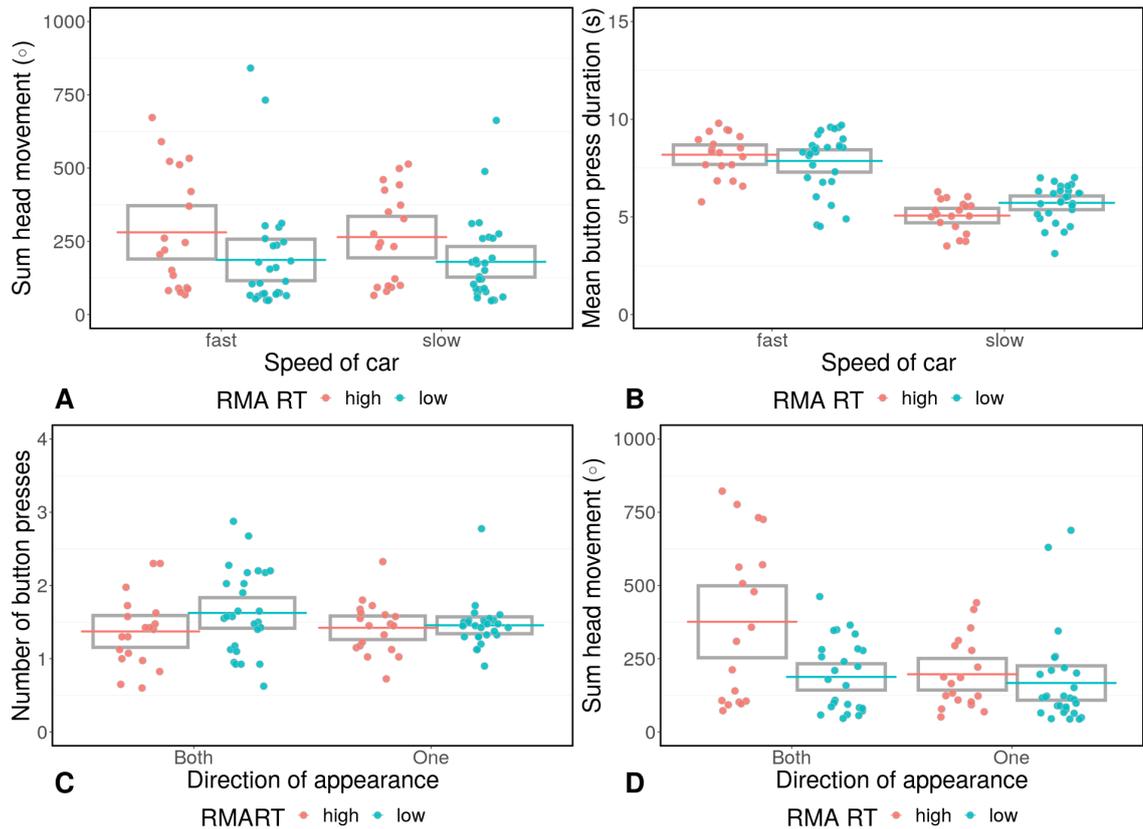


Figure C.9: Interaction between participants RTs on the RMA task and car speed on the amount of head movements (A) and on the duration of key presses (B) participants made. Interaction between RTs on the RMA task and car travel direction on the number of crossing decisions (C) and the amount of head movements (D) participants made.

There was an interaction between RTs on the RMA task and car speed on the duration of key presses and amount head movements participants made (Tables C.18, C.44). All participants made longer key presses when cars travelled quickly compared to slowly. This difference was larger for participants with slower RTs than participants with faster RTs on the RMA task (Tables C.25, and C.22; Figure C.9B). Participants with slow RTs on the RMA task made more head movements when cars travelled quickly compared to slowly (Table C.48, Figure C.9A). A simple effects LMM revealed that participants with fast RTs on the RMA task did not change their head movements when cars travelled quickly compared to slowly (Table C.47, Figure C.9B).

There was an interaction between RTs on the RMA task and the travel direction on the number of crossing decisions and amount of head movements participants

made (Tables C.7, and C.44). All participants made more crossing decisions and head movements when cars came from both directions compared to one direction only. The difference in crossing decisions was greater for participants with faster RTs than participants with slower RTs on the RMA task (Tables C.11, and C.10; Figure C.9C). The difference in crossing decisions was not significant for participants with slower RTs on the RMA task (Table C.10, Figure C.9C). The difference in head movements was greater for participants with slower RTs than participants with faster RTs on the RMA task (Tables C.48, and C.47; Figure C.9D).

## C.2 Supplementary Tables

### LMMs on the crossing decisions on Experiment 1

#### LMMs on the number of crossing decisions on Experiment 1

Table C.1: Results for the LMM run on the number of crossing decisions for Experiment 1. Significant results are highlighted in blue. Model fit: AIC = 2322.93, Pseudo-R<sup>2</sup> = 0.36. See Methods for the model that was run.

	$\beta$	Standard Error	T-value	P-value
RMA RT	1.12e-03	0.17	0.01	0.995
Car Speed	0.39	0.17	2.32	0.020
Lane number	0.18	0.20	0.88	0.378
Lane type	-0.15	0.20	-0.75	0.453
Car direction	-0.45	0.17	-2.72	0.007
Local switch cost	0.04	0.23	0.19	0.853
Global switch cost	-0.11	0.15	-0.71	0.479
BADS zoo map score	-0.02	0.05	-0.40	0.693
Age group	-0.05	0.12	-0.44	0.658
RMA RT * car speed	-0.12	0.09	-1.36	0.173
RMA RT * lane number	-0.04	0.11	-0.34	0.735
RMA RT * lane type	0.07	0.11	0.62	0.533
RMA RT * car direction	0.02	0.09	0.18	0.855
Local switch cost * car speed	-0.14	0.12	-1.12	0.265
Local switch cost * lane number	-0.07	0.15	-0.47	0.641
Local switch cost * lane type	0.06	0.15	0.41	0.685
Local switch cost * car direction	-0.04	0.12	-0.37	0.714
Global switch cost * car speed	-0.01	0.08	-0.13	0.895
Global switch cost * lane number	-0.05	0.09	-0.57	0.569
Global switch cost * lane type	-0.03	0.09	-0.35	0.728
Global switch cost * car direction	0.09	0.08	1.14	0.253
BADS zoo map score * car speed	5.58e-03	0.03	0.21	0.834
BADS zoo map score * lane number	-7.91e-03	0.03	-0.24	0.807
BADS zoo map score * lane type	2.60e-03	0.03	0.08	0.936
BADS zoo map score * car direction	0.01	0.03	0.56	0.573
Age group * car speed	0.07	0.06	1.18	0.237
Age group * lane number	-0.13	0.08	-1.73	0.084
Age group * lane type	0.13	0.08	1.66	0.097
Age group * car direction	0.04	0.06	0.68	0.498

## LMMs on the duration of key presses on Experiment 1

Table C.2: Results for the LMM run on the duration of key presses for Experiment 1. Significant results are highlighted in blue. Model fit: AIC = 7121.04, Pseudo-R<sup>2</sup> = 0.20. See Methods for the model that was run.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
RMA RT	-0.12	0.59	-0.20	0.845
Car Speed	1.09	0.92	1.19	0.235
Lane number	-0.73	1.12	-0.65	0.514
Lane type	0.41	0.12	0.37	0.715
Car direction	1.09	0.91	1.20	0.232
Local switch cost	1.27	0.80	1.59	0.112
Global switch cost	-0.06	0.52	-0.11	0.909
BADS zoo map score	0.44	0.18	2.46	0.014
Age group	-0.83	0.42	-1.99	0.048
RMA RT * car speed	0.06	0.48	0.12	0.906
RMA RT * lane number	0.45	0.59	0.76	0.447
RMA RT * lane type	-0.32	0.59	-0.54	0.589
RMA RT * car direction	0.04	0.48	0.08	0.936
Local switch cost * car speed	-0.02	0.66	-0.04	0.971
Local switch cost * lane number	0.34	0.79	0.43	0.665
Local switch cost * lane type	-0.41	0.80	-0.51	0.609
Local switch cost * car direction	-0.28	0.66	-0.43	0.668
Global switch cost * car speed	0.76	0.42	1.83	0.068
Global switch cost * lane number	-0.22	0.51	-0.44	0.660
Global switch cost * lane type	0.26	0.51	0.52	0.604
Global switch cost * car direction	-0.44	0.42	-1.06	0.288
BADS zoo map score * car speed	-0.53	0.15	-3.63	0.000
BADS zoo map score * lane number	0.11	0.18	0.65	0.517
BADS zoo map score * lane type	-0.05	0.18	-0.30	0.764
BADS zoo map score * car direction	0.15	0.14	1.04	0.298
Age group * car speed	-1.16	0.35	-3.37	0.001
Age group * lane number	0.41	0.42	0.99	0.324
Age group * lane type	-0.20	0.42	-0.47	0.638
Age group * car direction	0.51	0.34	1.49	0.137

## Simple effects LMM on the duration of key presses for YAs on Experiment 1

Table C.3: Results for the simple effects LMM run on the duration of key presses made by YAs on Experiment 1. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-1.34	0.18	-7.61	0.000
Car Direction	1.88	0.18	10.75	0.004

**Simple effects LMM on the duration of key presses for older adults on Experiment 1**

Table C.4: Results for the simple effects LMM run on the duration of key presses made by OAs on Experiment 1. Significant results are highlighted in blue

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	0.58	0.23	2.50	0.025
Car Direction	1.01	0.23	4.33	0.000

**Simple effects LMM on the duration of key presses for participants with high BADS zoo map scores on Experiment 1**

Table C.5: Results for simple effects LMM on duration of key presses by participants with high BADS zoo map scores on Experiment 1. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-1.23	0.17	-7.30	0.000
Car direction	1.78	0.17	10.60	0.000

**Simple effects LMM on the duration of key presses for participants with low BADS zoo map scores on Experiment 1**

Table C.6: Results for the simple effects LMM on the duration of key presses made by participants with low BADS zoo map scores on Experiment 1. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	0.72	0.26	2.80	0.010
Car direction	1.03	0.26	4.00	0.000

## LMMs on the crossing decisions on Experiment 2

### LMM for the number of crossing decisions

Table C.7: Results of the LMM run on the number of crossing decisions on Experiment 2. See Methods for the model that was run. Significant results are highlighted in blue. Model fit: AIC = 10107.71, Pseudo-R<sup>2</sup> = 0.29.

	$\beta$	Standard Error	T-value	P-value
RMA RT	0.25	0.17	1.49	0.140
Car speed	0.34	0.10	3.44	0.001
Traffic density	-0.04	0.03	-1.34	0.179
Car Direction – obscure	0.11	0.12	0.92	0.357
Car Direction – both	0.37	0.12	3.03	0.002
Pedestrian presence	-0.02	0.10	-0.24	0.809
BADS zoo map score	0.07	0.05	1.33	0.188
Age group	0.19	0.12	1.57	0.122
Global switch cost	-0.28	0.14	-1.91	0.060
Local switch cost	0.23	0.23	1.01	0.317
RMA RT * Car speeds	-0.03	0.05	-0.53	0.597
RMA RT * traffic density	1.15e-03	0.02	0.07	0.942
RMA RT * Car Direction – obscure	0.04	0.06	0.62	0.533
RMA RT * Car Direction – both	-0.14	0.06	-2.17	0.030
RMA RT * pedestrian presence	0.13	0.05	0.25	0.804
BADS zoo map score * car speed	-0.07	0.02	-4.42	0.000
BADS zoo map score * traffic density	-9.65e-03	4.81e-03	-2.01	0.045
BADS zoo map score * car direction – obscure	-3.05e-03	0.02	-0.16	0.872
BADS zoo map score * car direction – both	-0.07	0.02	-3.95	0.000
BADS zoo map score * pedestrian presence	5.17e-03	0.02	0.33	0.741
Age group * car speed	-0.08	0.04	-2.18	0.029
Age group * traffic density	-7.76e-03	0.01	-0.68	0.497
Age group * car direction – obscure	-0.04	0.04	-0.81	0.419
Age group * car direction – both	0.34	0.05	7.32	0.000
Age group * pedestrian presence	-0.04	0.04	-1.17	0.241
Global switch cost * car speed	-0.02	0.04	-0.47	0.638
Global switch cost * traffic density	0.03	0.01	2.30	0.022
Global switch cost * car direction – obscure	-0.11	0.05	-2.13	0.033
Global switch cost * car direction – both	-0.05	0.05	-0.90	0.370
Global switch cost * pedestrian presence	-0.05	0.04	-1.06	0.288
Local switch cost * car speed	-0.29	0.07	-3.85	0.000
Local switch cost * traffic density	-0.02	0.02	-0.90	0.369
Local switch cost * car direction – obscure	0.09	0.09	0.99	0.322
Local switch cost * car direction – both	0.09	0.09	0.95	0.343
Local switch cost * pedestrian presence	0.05	0.07	0.66	0.512

**Simple effects LMM for the number of crossing decisions made by YAs on Experiment 2**

Table C.8: Results of the simple effects LMM run on the number of crossing decisions made by YAs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-0.08	0.02	-4.19	0.000
Traffic density	-0.07	5.81e-03	-12.01	0.000
Car Direction – obscure	0.10	0.02	4.37	0.000
Car Direction – both	0.27	0.02	11.36	0.000

**Simple effects LMM for the number of crossing decisions made by OAs on Experiment 2**

Table C.9: Results of the simple effects LMM run on the number of crossing decisions made by OAs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	4.97e-04	0.03	0.02	0.999
Traffic density	-0.04	7.65e-03	-5.57	0.000
Car Direction – obscure	0.13	0.03	4.16	0.000
Car Direction – both	-0.07	0.03	-2.39	0.060

**Simple effects LMM for the number of crossing decisions made by participants with slow RTs on the RMA task on Experiment 2**

Table C.10: Results of the simple effects LMM on the number of crossing decisions by participants with slow RTs on the RMA task on Experiment 2. See Methods for the model that was run.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-0.02	0.03	-0.59	0.557
Traffic density	-0.05	7.72e-03	-6.18	0.000
Car Direction – obscure	0.10	0.03	3.24	0.001
Car Direction – both	-0.04	0.03	-1.32	0.187

**Simple effects LMM for the number of crossing decisions made by participants with fast RTs on the RMA task on Experiment 2**

Table C.11: Results of the simple effects LMM on number of crossing decisions by participants with fast RTs on the RMA task on Experiment 2. Significant results are highlighted in blue. See Methods for the model that was run.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	0.04	0.02	1.88	0.061
Traffic density	-0.07	5.86e-03	-11.66	0.000
Car Direction – obscure	0.10	0.02	4.21	0.000
Car Direction – both	0.02	0.02	6.64	0.000

**Simple effects LMM on the number of crossing decisions made by participants with high BADS zoo map scores on Experiment 2**

Table C.12: Results of the simple effects LMM on the number of crossing decisions made by participants with high BADS zoo map scores on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-0.07	0.02	4.24	0.000
Traffic density	-0.07	5.42e-03	-12.54	0.000
Car Direction – obscure	0.11	0.02	5.32	0.000
Car Direction – both	0.17	0.02	7.59	0.000

**Simple effects LMM on the number of crossing decisions made by participants with low BADS zoo map scores on Experiment 2**

Table C.13: Results of the simple effects LMM run on the number of crossing decisions made by participants with low BADS zoo map scores on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-5.89e-03	0.03	0.19	0.997
Traffic density	-0.04	9.29e-03	-4.58	0.000
Car Direction – obscure	0.06	0.04	1.77	0.244
Car Direction – both	0.12	0.04	3.25	0.004

**Simple effects LMM on the number of crossing decisions made by participants with large global switch costs on Experiment 2**

Table C.14: Results of the simple effects LMM run on the number of crossing decisions made by participants with large global switch costs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	0.08	0.02	3.56	0.001
Traffic density	-0.04	7.16e-03	-5.87	0.000
Car Direction – obscure	0.05	0.03	1.79	0.235
Car Direction – both	0.06	0.03	2.10	0.124

**Simple effects LMM on the number of crossing decisions made by participants with small global switch costs on Experiment 2**

Table C.15: Results of the simple effects LMM run on the number of crossing decisions made by participants with small global switch costs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-0.04	0.02	1.81	0.071
Traffic density	-0.07	6.17e-03	-11.97	0.000
Car Direction – obscure	0.13	0.02	5.36	0.000
Car Direction – both	0.22	0.02	8.69	0.000

**Simple effects LMM on the number of crossing decisions made by participants with large local switch costs on Experiment 2**

Table C.16: Results of the simple effects LMM run on the number of crossing decisions made by participants with large local switch costs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	0.07	0.03	2.47	0.049
Traffic density	-0.05	8.31e-03	-5.45	0.000
Car Direction – obscure	0.08	0.03	2.33	0.070
Car Direction – both	0.04	0.03	1.25	0.548

**Simple effects LMM on the number of crossing decisions made by participants with small local switch costs on Experiment 2**

Table C.17: Results of the simple effects LMM run on the number of crossing decisions made by participants with small local switch costs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	0.05	0.02	2.81	0.019
Traffic density	-0.07	5.66e-03	-12.15	0.000
Car Direction – obscure	0.11	0.02	4.88	0.000
Car Direction – both	0.02	0.02	9.15	0.000

## LMM for the duration of key presses on Experiment 2

Table C.18: Results for the LMM run on duration of key presses on Experiment 2. See Methods for the model that was run. Significant results are highlighted in blue. Model fit: AIC = 28080.07, Pseudo-R<sup>2</sup> = 0.32.

	$\beta$	Standard Error	T-value	P-value
RMA RT	0.31	0.56	0.57	0.572
Car speed	3.57	0.48	7.37	0.000
Traffic density	0.22	0.15	1.48	0.140
Car Direction – obscure	1.83	0.59	3.13	0.002
Car Direction – both	-0.91	0.60	-1.53	0.127
Pedestrian presence	-0.05	0.48	-0.10	0.920
BADS zoo map score	0.22	0.17	1.28	0.201
Age group	1.46	0.40	3.66	0.000
Global switch cost	-0.52	0.48	-1.09	0.279
Local switch cost	0.45	0.77	0.59	0.559
RMA RT * Car speeds	-0.86	0.25	-3.42	0.001
RMA RT * traffic density	-0.09	0.08	-1.20	0.231
RMA RT * Car Direction – obscure	0.43	0.31	-1.42	0.157
RMA RT * Car Direction – both	-0.03	0.31	-0.09	0.929
RMA RT * pedestrian presence	0.04	0.25	0.16	0.875
BADS zoo map score * car speed	0.08	0.08	1.10	0.274
BADS zoo map score * traffic density	0.01	0.02	0.58	0.565
BADS zoo map score * car direction – obscure	-0.13	0.09	-1.38	0.167
BADS zoo map score * car direction – both	-0.10	0.09	-1.08	0.281
BADS zoo map score * pedestrian presence	-2.90e-03	0.08	-0.04	0.970
Age group * car speed	-1.00	0.18	-5.47	0.000
Age group * traffic density	-0.08	0.06	-1.41	0.159
Age group * car direction – obscure	-0.73	0.22	-3.32	0.001
Age group * car direction – both	-1.18	0.23	-5.21	0.000
Age group * pedestrian presence	0.19	0.18	1.03	0.304
Global switch cost * car speed	1.09	0.22	4.98	0.000
Global switch cost * traffic density	0.02	0.07	0.23	0.819
Global switch cost * car direction – obscure	0.46	0.26	1.74	0.081
Global switch cost * car direction – both	0.32	0.27	1.20	0.230
Global switch cost * pedestrian presence	0.22	0.22	1.00	0.319
Local switch cost * car speed	0.73	0.36	2.00	0.046
Local switch cost * traffic density	-0.08	0.11	-0.74	0.459
Local switch cost * car direction – obscure	-0.36	0.43	-0.85	0.394
Local switch cost * car direction – both	-0.33	0.45	-0.72	0.469
Local switch cost * pedestrian presence	-0.44	0.36	-1.23	0.220

## Simple effects LMM for the duration of key presses made by YAs on Experiment 2

Table C.19: Results of the simple effects LMM run on the duration of key presses made by YAs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	Standard Error	T-value	P-value
Car speed	2.25	0.09	24.20	0.000
Traffic density	0.04	0.03	1.57	0.116
Car Direction – obscure	0.18	0.11	1.62	0.319
Car Direction – both	-2.41	0.11	-20.94	0.000

**Simple effects LMM for the duration of key presses made by OAs on Experiment 2**

Table C.20: Results of the simple effects LMM run on the duration of key presses made by OAs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	3.31	0.12	27.14	0.000
Traffic density	0.05	0.04	1.38	0.168
Car Direction – obscure	0.90	0.15	6.13	0.000
Car Direction – both	-1.06	0.15	-7.10	0.000

**Simple effects LMM for the duration of key presses on Experiment 2 made by participants with slow RTs on the RMA task**

Table C.21: Results of the simple effects LMM on the duration of key presses made by participants with slow RTs on the RMA task on Experiment 2. Significant results are highlighted in blue. See Methods for the model that was run.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	3.13	0.12	26.26	0.000
Traffic density	0.05	0.04	1.28	0.200
Car Direction – obscure	0.72	0.14	5.02	0.000
Car Direction – both	-1.44	0.15	-9.80	0.000

**Simple effects LMM for the duration of key presses on Experiment 2 made by participants with fast RTs on the RMA task**

Table C.22: Results of the simple effects LMM on the duration of key presses by participants with fast RTs on the RMA task on Experiment 2. See Methods for the model that was run.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	2.27	0.10	23.78	0.000
Traffic Density	0.05	0.03	1.73	0.084
Car Direction – obscure	0.27	0.12	2.36	0.019
Car Direction – both	-2.25	0.12	-19.16	0.000

**Simple effects LMM for the duration of key presses on Experiment 2  
made by participants with large global switch costs**

Table C.23: Results of the simple effects LMM on the duration of key presses made by participants with large global switch costs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	3.21	0.11	28.22	0.000
Traffic density	0.07	0.03	1.95	0.051
Car Direction – obscure	0.91	0.14	6.63	0.000
Car Direction – both	-1.41	0.14	-10.00	0.000

**Simple effects LMM for the duration of key presses on Experiment 2  
made by participants with small global switch costs**

Table C.24: Results of the simple effects LMM on the duration of key presses made by participants with small global switch costs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	2.19	0.10	22.35	0.000
Traffic density	0.04	0.03	1.39	0.165
Car Direction – obscure	0.13	0.12	1.09	0.653
Car Direction – both	-2.31	0.12	-19.16	0.000

**Simple effects LMM for the duration of key presses on Experiment 2  
made by participants with large local switch costs**

Table C.25: Results of the simple effects LMM on the duration of key presses made by participants with large local switch costs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	3.09	0.13	23.67	0.000
Traffic density	0.02	0.04	0.44	0.661
Car Direction – obscure	0.75	0.16	4.76	0.000
Car Direction – both	-1.60	0.16	-9.95	0.000

**Simple effects LMM for the duration of key presses on Experiment 2  
made by participants with small local switch costs**

Table C.26: Results of the simple effects LMM on the duration of key presses made by participants with small local switch costs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	2.36	0.09	25.95	0.000
Traffic density	0.07	0.03	2.38	0.018
Car Direction – obscure	0.30	0.11	2.68	0.028
Car Direction – both	-2.11	0.11	-18.80	0.000

## LMMs on TTI on Experiment 1

Table C.27: Results for the LMM run on TTI for Experiment 1. See Methods for the model that was run. Significant results are highlighted in blue. Model fit: AIC = 4730.78, Pseudo-R<sup>2</sup> = 0.55.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
RMA RT	-0.09	0.58	-0.15	0.878
Car Speed	-1.17	0.53	-2.19	0.029
Car direction	-1.85	0.52	3.53	0.000
Lane number	-0.43	0.64	-0.67	0.501
Lane type	0.01	0.63	0.02	0.986
Local switch cost	-1.76	0.85	-2.06	0.042
Global switch cost	0.62	0.51	1.23	0.223
BADS zoo map score	-0.47	0.18	-2.66	0.010
Age group	1.02	0.42	2.43	0.018
RMA RT * car speed	-0.68	0.30	-2.26	0.024
RMA RT * car direction	0.02	0.30	0.05	0.957
RMA RT * lane number	0.19	0.36	0.52	0.607
RMA RT * lane type	0.16	0.35	0.45	0.653
Local switch cost * car speed	0.04	0.56	0.08	0.940
Local switch cost * car direction	0.18	0.50	0.36	0.716
Local switch cost * lane number	-0.04	0.62	-0.06	0.953
Local switch cost * lane type	0.59	0.60	0.99	0.325
Global switch cost * car speed	0.43	0.28	1.57	0.117
Global switch cost * car direction	-0.18	0.27	-0.69	0.492
Global switch cost * lane number	0.11	0.33	0.34	0.736
Global switch cost * lane type	-0.32	0.31	-1.04	0.297
BADS zoo map score * car speed	0.30	0.09	3.25	0.001
BADS zoo map score * car direction	-0.25	0.09	-2.81	0.005
BADS zoo map score * lane number	0.04	0.11	0.36	0.719
BADS zoo map score * lane type	-0.03	0.11	-0.26	0.794
Age group * car speed	-0.82	0.22	-3.68	0.000
Age group * car direction	0.52	0.22	2.37	0.018
Age group * lane number	0.37	0.27	1.40	0.163
Age group * lane type	0.04	0.26	0.17	0.864

## Simple effects LMM for YAs on TTI on Experiment 1

Table C.28: Simple effects LMM run on the TTI for YAs on Experiment 1. Significant results are highlighted in blue

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-0.97	0.09	-10.26	0.000
Car direction	-1.02	0.09	-10.90	0.000

### Simple effects LMM for OAs on the TTI on Experiment 1

Table C.29: Simple effects LMM on the TTI for OAs on Experiment 1. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-2.15	0.10	-11.38	0.000
Lane number	-1.70	0.19	-9.19	0.000

### Simple effects LMM for participants with low BADS zoo map scores on TTI on Experiment 1

Table C.30: Simple effects LMM on the TTI for participants with low BADS zoo map scores on Experiment 1. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-2.06	0.22	9.57	0.000
Car Direction	-1.78	0.21	-8.48	0.000

### Simple effects LMM for participants with high BADS zoo map scores on TTI on Experiment 1

Table C.31: Simple effects LMM on the TTI decisions for participants with high BADS zoo map scores on Experiment 1. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-1.10	0.09	-11.77	0.000
Car direction	-1.08	0.09	-11.64	0.000

### Simple effects LMM for participants with fast RTs on the RMA task on TTI on Experiment 1

Table C.32: Simple effects LMM on the TTI decisions for participants with fast RTs on the RMA task on Experiment 1. Significant results are highlighted in blue. See Methods for the model that was run.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-1.01	0.11	9.45	0.000
Car direction	-1.11	0.11	-10.49	0.000

## Simple effects LMM for participants with slow RTs on the RMA task on time TTI on Experiment 1

Table C.33: Simple effects LMM on TTI decisions for participants with slow RTs on the RMA task on Experiment 1. Significant results are highlighted in blue. See Methods for the model that was run.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-1.76	0.15	-11.67	0.000
Car direction	-1.40	0.15	-9.36	0.000

## LMM for TTI on Experiment 2

Table C.34: Results for the LMM on TTI on Experiment 2. See Methods for the model that was run. Significant results are highlighted in blue. Model fit: AIC = 33367.01, Pseudo-R<sup>2</sup> = 0.39.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
RMA RT	-0.18	0.52	-0.34	0.736
Car speed	-2.32	0.36	-6.92	0.000
Traffic density	-0.07	0.10	-0.69	0.491
Car Direction – obscure	-1.70	0.39	-4.32	0.000
Car Direction – both	0.45	0.36	1.25	0.211
Pedestrian presence	-0.12	0.30	-0.39	0.701
BADS zoo map score	-0.54	0.16	-3.29	0.002
Age group	2.04	0.39	5.27	0.000
Global switch cost	0.56	0.44	1.26	0.212
Local switch cost	-1.33	0.77	-1.71	0.090
RMA RT * Car speed	-0.24	0.18	-1.38	0.169
RMA RT * traffic density	-0.06	0.05	-1.23	0.219
RMA RT * Car Direction – obscure	0.17	0.21	0.80	0.423
RMA RT * Car Direction – both	-0.37	0.19	-1.95	0.051
RMA RT * pedestrian presence – present	0.14	0.16	0.88	0.378
BADS zoo map score * car speed	0.26	0.06	4.36	0.000
BADS zoo map score * traffic density	1.26e-03	0.02	0.08	0.940
BADS zoo map score * car direction – obscure	0.09	0.07	1.31	0.189
BADS zoo map score * car direction – both	0.15	0.06	2.43	0.015
BADS zoo map score * pedestrian presence	-0.02	0.05	-0.41	0.684
Age group * car speed	-0.78	0.15	-5.04	0.000
Age group * traffic density	-0.03	0.04	-0.65	0.514
Age group * car direction – obscure	-0.72	0.17	-4.25	0.000
Age group * car direction – both	-0.55	0.17	-3.33	0.001
Age group * pedestrian presence	-0.08	0.13	-0.57	0.570
Global switch cost * car speed	0.14	0.16	0.89	0.373
Global switch cost * traffic density	0.02	0.04	0.35	0.725
Global switch cost * car direction – obscure	-0.22	0.18	-1.18	0.237
Global switch cost * car direction – both	0.20	0.17	1.17	0.240
Global switch cost * pedestrian presence	-0.07	0.14	-0.52	0.603
Local switch cost * car speed	-0.06	0.37	-0.16	0.877
Local switch cost * car direction – obscure	0.96	0.47	2.03	0.042
Local switch cost * car direction – both	1.85	0.37	4.98	0.000
Local switch cost * traffic density	0.06	0.11	0.52	0.603
Local switch cost * pedestrian presence	0.08	0.34	0.23	0.821

### Simple effects LMM for YAs on TTI on Experiment 2

Table C.35: Simple effects LMM run on the TTI for YAs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-1.86	0.07	-28.07	0.000
Traffic density	-0.14	0.02	-7.37	0.000
Car Direction – obscure	-1.03	0.08	-13.22	0.000
Car Direction – both	0.89	0.07	13.00	0.000

### Simple effects LMM for OAs on TTI on Experiment 2

Table C.36: Simple effects LMM run on the TTI for OAs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-2.83	0.11	-24.70	0.000
Traffic density	-0.18	0.03	-5.75	0.000
Car Direction – obscure	-1.68	0.12	-13.88	0.000
Car Direction – both	0.53	0.12	4.31	0.000

### Simple effects LMM on the TTI for participants with small local switch costs on Experiment 2

Table C.37: Simple effects LMM run on the TTI for participants with small local switch costs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-1.88	0.07	-26.88	0.000
Traffic density	-0.14	0.02	-7.32	0.000
Car Direction – obscure	-1.20	0.08	-14.79	0.000
Car Direction – both	0.78	0.07	10.45	0.000

### Simple effects LMM on the TTI for participants with large local switch costs on Experiment 2

Table C.38: Simple effects LMM run on the TTI for participants with large local switch costs on Experiment 2. Significant results are highlighted in blue

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-2.59	0.10	25.83	0.000
Traffic density	-0.16	0.03	-5.67	0.000
Car Direction – obscure	-1.28	0.11	-11.45	0.000
Car Direction – both	0.88	0.11	8.38	0.000

### Simple effects LMM on the TTI for participants with high BADS zoo map scores on Experiment 2

Table C.39: Simple effects LMM run on the TTI for participants with high BADS zoo map scores on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-1.91	0.06	-30.12	0.000
Traffic density	-0.15	0.02	-8.39	0.000
Car Direction – obscure	-1.13	0.07	-15.59	0.000
Car Direction – both	0.88	0.07	13.24	0.000

## Simple effects LMM on TTI for participants with low BADS zoo map scores on Experiment 2

Table C.40: Simple effects LMM run on the TTI for participants with low BADS zoo map scores on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-2.72	0.13	-21.05	0.000
Traffic density	-0.17	0.04	-4.71	0.000
Car Direction – obscure	-1.53	0.15	-10.20	0.000
Car Direction – both	0.53	0.13	4.04	0.000

## LMMs for the amount of head movements on Experiment 1

Table C.41: Results for the LMM run on the amount of head movements participants made on Experiment 1. See Methods for the model that was run. Significant results are highlighted in blue. Model fit: AIC = 17264.96, Pseudo-R<sup>2</sup> = 0.67.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
RMA RT	-8.42	60.27	-0.14	0.890
Car Speed	-37.59	29.42	-1.28	0.202
Lane number	24.49	36.02	0.68	0.497
Lane type	-28.47	35.92	-0.79	0.428
Car direction	-7.47	29.31	-0.26	0.799
Local switch cost	-6.67	81.68	-0.08	0.935
Global switch cost	-14.45	52.07	-0.28	0.783
BADS zoo map score	-7.83	18.11	-0.43	0.667
Age group	110.13	43.04	2.56	0.014
RMA RT * car speed	20.63	16.43	1.26	0.209
RMA RT * lane number	-20.23	20.17	-1.00	0.316
RMA RT * lane type	31.64	20.05	1.58	0.115
RMA RT * car direction	-28.15	16.42	-1.72	0.087
Local switch cost * car speed	19.57	22.51	0.87	0.385
Local switch cost * lane number	26.35	26.97	0.98	0.329
Local switch cost * lane type	-21.12	27.24	-0.78	0.438
Local switch cost * car direction	96.41	22.36	4.31	0.000
Global switch cost * car speed	-3.24	14.31	-0.23	0.821
Global switch cost * lane number	21.45	17.33	1.24	0.216
Global switch cost * lane type	-13.34	17.29	-0.77	0.440
Global switch cost * car direction	19.84	14.25	1.39	0.164
BADS zoo map score * car speed	-0.42	4.96	-0.08	0.933
BADS zoo map score * lane number	2.66	6.03	0.44	0.659
BADS zoo map score * lane type	-4.95	6.06	-0.82	0.414
BADS zoo map score * car direction	6.79	4.92	1.38	0.168
Age group * car speed	9.82	11.74	0.84	0.403
Age group * lane number	-26.76	14.25	-1.88	0.061
Age group * lane type	2.45	14.27	0.17	0.864
Age group * car direction	-11.44	11.71	-0.98	0.329

### Simple effects LMM for participants with small local switch costs on head movements on Experiment 1

Table C.42: Simple effects LMM run on the amount of head movements made by participants with small local switch costs on Experiment 1. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-8.00,	3.88	-2.06	0.077
Car Direction	1.71	3.99	0.45	0.880

### Simple effects LMM for participants with large local switch costs on head movements on Experiment 1

Table C.43: Simple effects LMM on the amount of head movements made by participants with large local switch costs on Experiment 1. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	12.14	7.37	1.65	0.188
Car Direction	-11.62	7.21	-1.61	0.203

## LMMs on the amount of head movements on Experiment 2

### LMM for the amount of head movements made on Experiment 2

Table C.44: Results for the LMM run on the amount of head movements participants made on Experiment 2. See Methods for the model that was run. Significant results are highlighted in blue. Model fit: AIC = 71413.21, Pseudo-R<sup>2</sup> = 0.76.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
RMA RT	-8.19	61.30	-0.13	0.894
Car speed	-6.44	16.87	-0.38	0.703
Traffic density	-5.67	5.20	-1.09	0.276
Car Direction – obscure	-12.79	20.99	-0.61	0.542
Car Direction – both	-72.46	21.06	-3.44	0.001
Pedestrian presence	-18.24	17.98	-1.02	0.310
BADS zoo map score	-7.16	18.45	-0.39	0.700
Age group	119.24	43.80	2.72	0.009
Global switch cost	4.93	52.82	0.09	0.926
Local switch cost	-59.27	83.16	-0.71	0.479
RMA RT * Car speed	24.98	9.42	2.65	0.008
RMA RT * traffic density	0.32	2.90	0.11	0.913
RMA RT * Car Direction – obscure	14.38	11.81	1.22	0.223
RMA RT * Car Direction – both	70.37	11.77	5.98	0.000
RMA RT * pedestrian presence – present	5.66	9.44	0.60	0.549
BADS zoo map score * car speed	-6.84	2.84	-2.41	0.016
BADS zoo map score * traffic density	-0.20	0.87	-0.23	0.820
BADS zoo map score * car direction – obscure	-9.69	3.45	-2.81	0.005
BADS zoo map score * car direction – both	10.16	3.47	2.93	0.003
BADS zoo map score * pedestrian presence	5.04	2.84	1.77	0.076
Age group * car speed	33.32	6.76	4.93	0.000
Age group * traffic density	-1.07	2.07	-0.51	0.607
Age group * car direction – obscure	-20.78	8.32	-2.50	0.013
Age group * car direction – both	216.70	8.30	26.11	0.000
Age group * pedestrian presence	4.11	6.72	0.61	0.541
Global switch cost * car speed	-11.20	8.14	-1.38	0.169
Global switch cost * traffic density	-0.13	2.50	-0.05	0.958
Global switch cost * car direction – obscure	13.32	9.90	1.35	0.179
Global switch cost * car direction – both	25.90	9.94	2.61	0.009
Global switch cost * pedestrian presence	-1.50	8.14	-0.19	0.853
Local switch cost * car speed	-43.78	12.88	-3.40	0.001
Local switch cost * car direction – obscure	11.21	3.96	2.83	0.004
Local switch cost * car direction – both	69.07	15.74	4.39	0.000
Local switch cost * traffic density	-94.48	15.70	-6.02	0.000
Local switch cost * pedestrian presence	3.32	7.87	-0.42	0.673

## Simple effects LMM on the amount of head movements made by YAs on Experiment 2

Table C.45: Simple effects LMM run on the amount of head movements made by YAs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-6.67	1.96	-3.40	0.003
Traffic density	-3.36	0.60	-5.59	0.000
Car Direction – obscure	-0.57	2.38	-0.24	0.994
Car Direction – both	46.60	2.39	19.54	0.000

## Simple effects LMM on the amount of head movements made by OAs on Experiment 2

Table C.46: Simple effects LMM run on the amount of head movements made by OAs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	31.92	7.03	4.54	0.000
Traffic density	-2.13	2.16	-0.99	0.324
Car Direction – obscure	6.18	8.44	0.73	0.863
Car Direction – both	288.10	8.44	34.15	0.000

## Simple effects LMM for participants with fast RTs on the RMA task on head movements on Experiment 2

Table C.47: Simple effects LMM on head movements for participants with fast RTs on the RMA task on Experiment 2. Significant results are highlighted in blue. See Methods for the model that was run.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	1.29	3.06	0.42	0.673
Traffic density	-2.31	0.94	-2.46	0.014
Car Direction – obscure	-3.03	3.78	-0.80	0.423
Car Direction – both	88.25	3.79	23.32	0.000

**Simple effects LMM for participants with slow RTs on the RMA task on head movements on Experiment 2**

Table C.48: Simple effects LMM on head movements for participants with slow RTs on the RMA task on Experiment 2. See Methods for the model that was run.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	15.02	6.34	2.37	0.018
Traffic density	-4.57	2.00	-2.34	0.019
Car Direction – obscure	5.37	8.08	0.67	0.506
Car Direction – both	201.39	8.07	24.97	0.000

**Simple effects LMM on the amount of head movements made by participants with low BADS zoo map scores on Experiment 2**

Table C.49: Simple effects LMM run on the amount of head movements made by participants with low BADS zoo map scores on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	30.40	7.56	4.02	0.000
Traffic density	-2.27	2.34	-0.97	0.332
Car Direction – obscure	26.85	9.13	2.94	0.013
Car Direction – both	173.10	9.42	18.38	0.000

**Simple effects LMM on the amount of head movements made by participants with high BADS zoo map scores on Experiment 2**

Table C.50: Simple effects LMM run on the amount of head movements made by participants with high BADS zoo map scores on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	-2.48	3.13	-0.79	0.833
Traffic density	-2.86	0.96	-2.98	0.003
Car Direction – obscure	-10.62	3.82	-2.78	0.021
Car Direction – both	110.82	3.82	28.98	0.000

**Simple effects LMM on the amount of head movements made by participants with small global switch costs on Experiment 2**

Table C.51: Simple effects LMM run on the amount of head movements made by participants with small global switch costs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	2.46	3.09	0.79	0.832
Traffic density	-1.96	0.95	-2.07	0.038
Car Direction – obscure	-6.60	3.77	-1.75	0.251
Car Direction – both	79.94	3.81	20.98	0.000

**Simple effects LMM on the amount of head movements made by participants with large global switch costs on Experiment 2**

Table C.52: Simple effects LMM run on the amount of head movements made by participants with large global switch costs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	12.60	6.09	2.07	0.131
Traffic density	-4.10	1.87	-2.19	0.029
Car Direction – obscure	11.64	7.50	1.55	0.355
Car Direction – both	206.56	7.56	27.33	0.000

**Simple effects LMM on the amount of head movements made by participants with small local switch costs on Experiment 2**

Table C.53: Simple effects LMM run on the amount of head movements made by participants with small local switch costs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	3.88	3.27	1.19	0.588
Traffic density	-3.30	1.00	-3.30	0.001
Car Direction – obscure	-3.83	3.99	-0.96	0.737
Car Direction – both	105.98	3.99	26.57	0.000

## Simple effects LMM on the amount of head movements made by participants with large local switch costs on Experiment 2

Table C.54: Simple effects LMM run on the amount of head movements made by participants with large local switch costs on Experiment 2. Significant results are highlighted in blue.

	$\beta$	<i>Standard Error</i>	<i>T-value</i>	<i>P-value</i>
Car speed	11.27	6.87	1.64	0.307
Traffic density	-1.02	2.10	-0.49	0.626
Car Direction – obscure	6.65	8.43	0.79	0.835
Car Direction – both	184.16	8.35	22.06	0.000

### C.3 Response to examiners' comments

#### C.3.1 Response to external examiner's comments

Was the tracker calibrated on all three screens?

The tracker was initially calibrated using a custom calibration procedure presented on all three screens. This procedure involved presenting circles with a break on the left or right side and a dot in the middle (Figure C.10) at random locations on all three screens. Participants had to look at the circle and indicate whether the break in the circle was on the right or left hand side using the left and right arrow keys on the keyboard. While participants did this their eye movements were recorded. This was followed by the Eyelink calibration procedure performed only on the centre screen.

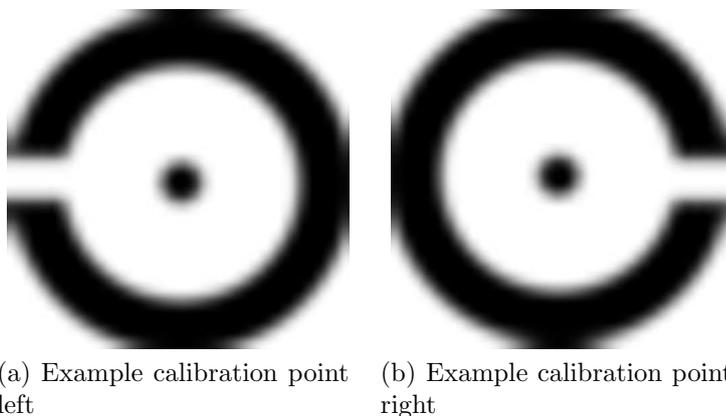


Figure C.10: Example calibration points for the three screen calibration of the Eyelink II. (a) Example calibration point with the break in the circle on the left. (b) Example calibration point with the break in the circle on the right

I have added the calibration procedure to the methods section of Chapter 4.

**Since the eye movement data is missing for these experiments (see general comment), a lot more information could be given here about why this is difficult and what the data look like**

The Eyelink II is set up to be used for one screen, so gaze coordinates can only be determined for one screen. To use a three screen set up one needs to use head motion and position data measured by a separate motion tracker. One also needs to use the head referenced position data (HREF). HREF measures eye rotation angles relative to the head. However, the output data is not a rotation angle of the eye but x and y coordinates which define a point on the HREF plane which is a constant 15,000 units away from the participant. The eye rotation angle can then be determined from the coordinates using the following equation provided in the Eyelink II manual:

$$\text{angle} = \text{acos} \left( \frac{(f^2 + x1^2 + y1^2)}{\left( \sqrt{(f^2 + x1^2 + y1^2)} * \sqrt{(f^2 + x2^2 + y2^2)} \right)} \right);$$

f is the constant distance from the participants' eyes to the HREF plane, and x and y are the HREF x and y coordinate values. During the calibration the HREF values are scaled and from there you can related the HREF coordinates to real world coordinates. A new calibration procedure was required to ensure that the HREF values are scaled appropriately for the three screen environment I used. One of my supervisors had managed to develop a calibration procedure for three screens, as mentioned above, but we had not yet developed a way to scale the HREF coordinates after the calibration procedure was completed. Once this is completed then I will be able to analyse the eye tracking data.

I have added the above details about the missing eye movement data to the methods section of Chapter 4.

**The bit about DTI and TTI should be rephrased because you say that you want to look at them separately, but you then say that you designed the task so that they were perfectly correlated. It would be better to explain that this is something you could/should have done differently**

This has been altered to the following: “ Previously, it has been shown that YAs and OAs are able to make decisions based on a combination of time and distance to impact (DTI; Lobjois & Cavallo, 2007). As my study had cars moving at a constant speed with the same size gaps between the cars, I was not able to investigate this as the DTI would be perfectly correlated with the TTI. To investigate this I could have had cars move with different sized gaps between them, moving with changing speeds, or accelerations.”

**Here, but also elsewhere in the thesis, I found it difficult to follow some of the LMM models being fit. One issue is that overall model fit is not reported. I normally do this by testing nested models and using maximum likelihood comparisons, which is what most LMER tutorials do, I think**

I have added model fit values (AIC and Pseudo-R<sup>2</sup>) to the table captions.

**The other issue is that the reader has to dig deep into the many tables in the appendix to find these interactions, I would recommend putting some of the key numbers in the main text**

I have added main effect and interaction values to the results of experiments one and two in Chapter 4.

### **C.3.2 Response to internal examiner's comments**

**Why complicate experiment 2 stimuli with so many factors? Up to this point the progression from one experiment to the next was gradual which helped with analysis and interpretation**

The reason experiment 2 had so many factors was for a combination of replicating previous findings and expanding upon them. In Chapter 3 I found that in simple situations older adults without declining executive functions were able to make safe crossing decisions. However, these older adults may have more difficulties in more complex road crossing situations, as older adults typically have slower processing speeds and lower cognitive loads (Park & Festini, 2017; Phillips et al., 2003) which may affect them when traffic density is high, cars are travelling from a number of different directions or cars are travelling quickly. I wanted to start with the same factors that I used in Chapter 3, pedestrian presence and traffic density. Pedestrian presence captured the eye movement of older adults in Chapter 2 but did not impact on crossing decisions. As mentioned in Chapter 3, this may be because the task was simple enough that older adults could be distracted by pedestrians but still be able to disengage their attention from the pedestrians with enough time to take in the information they need to make a safe crossing decision. However, if older adults were distracted when multiple cars are travelling down the road or the cars are travelling quickly they may not be able to take in enough information or react quickly enough to make a safe crossing decision. Similarly with traffic density, although it showed no impact on crossing behaviour in Chapter 2, it may have an impact in combination with an additional factor such as car speed or cars travelling from multiple directions. I chose to combine the factors from Chapter 2 with additional factors of car speed, cars travelling in the far lane or both lanes, and cars travelling from an obscured direction. These factors were chosen based on the results from previous studies which had all shown they had an impact on the crossing behaviour of older adults (Dommes et al., 2013; Geraghty et al., 2016; Lobjois & Cavallo, 2007; Oxley et al., 1997, 2005). I felt it would be more appropriate to test all these combinations of factors in one study rather than in three separate studies.

**It is a shame that the eye movement data were not useful. I don't completely understand what the issue with data processing is. Is it the case that gaze coordinates are not possible to determine in Jan's lab setup?**

The Eyelink II is set up to be used for one screen, so gaze coordinates can only be determined for one screen. To use a three screen set up one needs to use head motion and position data measured by a separate motion tracker. One also needs to use the head referenced position data (HREF). HREF measures eye rotation angles relative to the head. However, the output data is not a rotation angle of the eye but x and y coordinates which define a point on the HREF plane which is a constant 15,000 units away from the participant. The eye rotation angle can then be determined from the coordinates using the following equation provided in the Eyelink II manual:

$$\text{angle} = \text{acos} \left( \frac{f^2 + x_1^2 + y_1^2}{\sqrt{(f^2 + x_1^2 + y_1^2) * (f^2 + x_2^2 + y_2^2)}} \right);$$

f is the constant distance from the participants' eyes to the HREF plane, and x and y are the HREF x and y coordinate values. During the calibration the HREF values are scaled and from there you can related the HREF coordinates to real world coordinates. A new calibration procedure was required to ensure that the HREF values are scaled appropriately for the three screen environment I used. One of my supervisors had managed to develop a calibration procedure for three screens, as mentioned above, but we had not yet developed a way to scale the HREF coordinates after the calibration procedure was completed. Once this is completed then I will be able to analyse the eye tracking data.

**If you could change something about chapter 4 exp 1 what would it be?**

I would not change anything about Chapter 4 experiment one. I think that it was a well controlled study that allowed me to address critical confounds. Specifically, experiment one allowed me to separate any effects of cars travelling along the far lane from effects of cars travelling from both directions. The study also allowed me to differentiate any effects of cars travelling in both lanes from cars travelling in one lane only. Previous studies showed that participants had difficulties making

decisions for traffic travelling in the far lane, only used traffic situations coming from both directions (Geraghty et al., 2016; Oxley et al., 1997, 2005). Therefore, it is not possible to differentiate the impact of making decisions on both lanes from making decisions on only the far lane, and two cars versus one car. The design of Chapter 4 experiment one allowed me to differentiate these effects. However, the experiment did produce a large number of findings and organising the narrative was challenging but it does not take anything away from the design of the experiment.

**It would be good to provide some context about the BADS scores and RMA scores. I assume higher is better but the figures show these can only be between 0 and 4**

For the BADS zoo map scores, higher is better, but they only range from 0 to 4. For the RMA scores, accuracy was reported as 0 or 1 for each trial. The local switch cost on scores was the difference between average accuracy on switch trials and average accuracy on non-switch trials. The global switch cost on score was the difference between the average accuracy on blocks where participants switch between tasks and the average accuracy on blocks where participants were doing the same task. These values could range anywhere from 0 to 1.

I have added further details on the scoring of the executive functioning tests to the executive function tests subsection of the methods for Chapter 4.

**Regarding the null findings in exp 1 for number of lanes and near or far lane, does this mean that crossings are riskier when cars are travelling in both lanes or in the far lane since such cases would require more time to clear the cars?**

It is possible that these decisions could be considered risky, as they should leave more time to cross the far lane as this takes more time to cross than the near lane. However, this assumes that participants do not leave enough time to cross both lanes as a precaution or habit when they cross the near lane. Therefore, as the results are not significantly different rather than a reduction in TTI, then I would err on the side of these decisions being safe crossing decisions.

Perhaps figures showing data could also indicate what differences were significant

I have only shown the significant results in the figures.

# Appendix D

## Supplementary materials for chapter 5

### D.1 Supplementary Figures

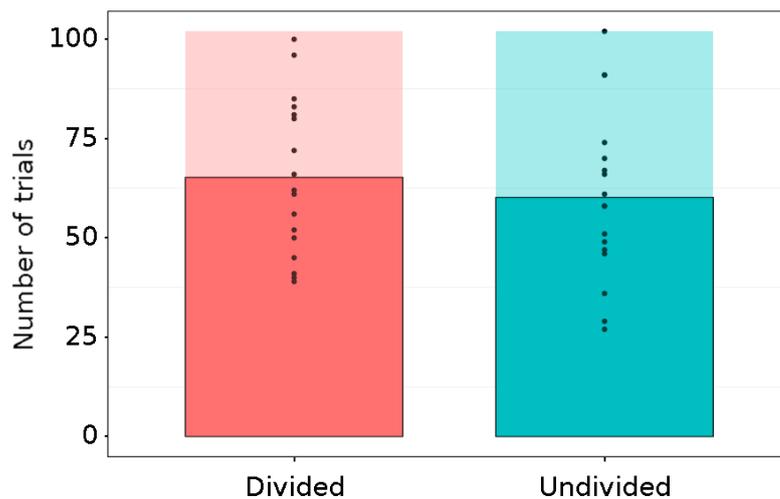


Figure D.1: Trials were excluded due to unreliable tracking of the targets in both conditions from a total of 102 presented in each condition. Dots represent accepted trial numbers for each participant.

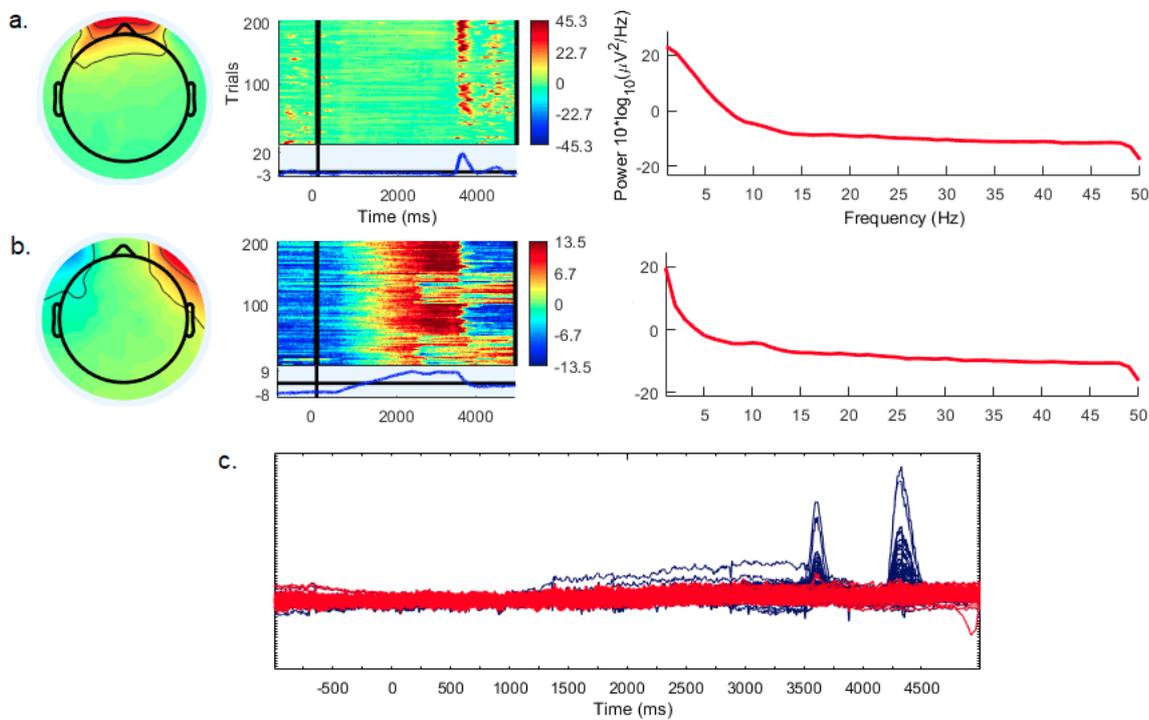


Figure D.2: Distortions isolated and removed through the ICA process encompassed (a.) eye-blinks, and (b.) eye-movements involving saccades (sharp onset/offset activity), as well as smooth pursuit (slow drift). Fig c represents a single-trial example of uncorrected raw EEG (blue) and ICA corrected EEG (blinks, saccades, and drift removed) (red).

## D.2 Response to examiner’s comments

### D.2.1 Response to external examiner’s comments

“Part of such a dynamic involves attention directed to...” I would rephrase this to say “attention BEING directed to” or similar

This sentence should be changed to: “Part of such a dynamic involves attention being directed to what we are directly foveating (overt attention), as well as attention directed to areas outside our foveal fields in our parafoveal or peripheral visual fields in the form of covert attention (Posner, 1980). ”

I think the “goal” portion of the display should be described as circular, not spherical, unless there was a 3D element I was missing

The sentence starting “Participants were instructed to follow...” should be changed to: “Participants were instructed to follow a moving target as it moved across a

computer screen and to press a keyboard button when the target entered an elliptical “goal” portion of the screen.”

**The sentences around this point are not very clear about the time period analysed. At first it says there was a period of interest, and then it says “Analyses were performed on the entire trial”. So is the whole trial included or not?**

The analyses were performed on the whole trial but focused on two periods of interest. One main period of interest where I hypothesised the difference in the power of the 30Hz signal between the divided and undivided attention condition would occur. The other time period of interest occurred just before the main time period of interest. The sentences “The time-window leading up to the possible presentation of a second target thus formed the period of interest for our analysis, where shifts of attention relating to participants’ condition-related expectations were predicted to occur. Analyses were performed on the entire trial time-range, with particular focus on the period of interest where the participants’ eye-gaze was directly over the moving targets. Analyses on the time period preceding this period are provided with the caveat that the conditions during this time period were uncontrolled for low-level visual properties relating to where the stimuli appeared in the participants’ visual field.”

Should be changed to the following to clarify the time periods analysed: “Analyses were performed on the entire trial time-range but focusing on two time-windows. The time-window leading up to the possible presentation of a second target formed the main period of interest for our analysis, where shifts of attention relating to participants’ condition-related expectations were predicted to occur. The time period preceding this period was also analysed with the caveat that the conditions during this time period were uncontrolled for low-level visual properties relating to where the stimuli appeared in the participants’ visual field.

**The divided attention condition only had an actual 2nd target on 2/3 of the trials. Were all the trials still included? Or only ones with/without a target? Would that make a difference?**

All the trials were still included, even trials without a second target. This would not make a difference to the results as the main time period of interest was prior to the appearance of the second target. Moreover, the task is still the same in both conditions, participants still need to covertly search for the second target even if one does not appear. Therefore, I would still expect a drop in the power of the 30Hz signal in the same time period as on trials where the second target appears.

**One thing I don't completely understand about the procedure is that participants are required to overtly pursue the second target. I'm a bit curious as to why this is necessary and why some other sort of purely covert instruction wasn't used (e.g., covertly track 2nd target, or covertly attend to spot an onset or discriminate a target or something)**

In this study one of my aims was to see whether I could identify the point when participants shift their sensory processing from only overtly attending a target to overtly attending a moving target and covertly attending to spot the onset of a second target. In this situation I would expect that the power of the SSVEP signal would drop as attentional resources are being spread between overt and covert attention, rather than focused on the participant's overt attention. Once participants have detected the onset of the second target, they refocus all their attentional resources (overt and covert) onto the second target, and I would expect the power of the SSVEP signal to return to the same levels as when participants overtly tracked the first target. Which is what I found in the study. If participants covertly tracked the second target and overtly attended the first target, I would expect the SSVEP power signal to stay low and not increase as it did in this experiment. However, once the first target has disappeared it is unclear where the participants should be overtly attending while they are covertly tracking the second target. Participants could be instructed to overtly attend the goal area and covertly track the second tar-

get. However, as the goal area does not flicker no SSVEP signal would be produced. Therefore, it is unclear whether the continued low power in the SSVEP signal is because the target has disappeared or because the participant's attention is divided between attending the goal area and the second target. To eliminate this confound I thought it would be best if participants covertly attend for the onset of the second target and once they have detected it overtly attend it. Then, I predicted I would see a drop in the power of the SSVEP signal followed by an increase, where the drop in power could only be due to the dividing of attentional resources.

Therefore, either type of task would most likely produce the same result. However, once the second target has appeared participants may find it easier to overtly track the second target rather than covertly track it.

**4 participants are rejected due to insufficient trials. Is this 4 more in addition to the 5 described in the Participants section? What was the final N?**

No, these were the same as the ones described in the participant section. The final N was 17.

**Later on we hear of 39% trials rejected. Is this from the valid participants? I'm curious as to why so many trials were rejected given that the tracking task does not seem particularly difficult**

This was from the valid participants. Even though overtly tracking the moving target is easy, covertly monitoring an empty area for the appearance of a target is much more difficult. As overt and covert attention are tightly linked, allocating covert attention on the appearing point is likely to have triggered a number of saccades. Moreover, in some trials, the participants might have thought that the second target appeared when that was not the case. Finally, participants might have anticipated their saccades to the second target in some trials. Other trials were also removed for noisy EEG recordings.

**Here the authors report what I thought the EyeLink default detection parameters were, but note that these are different from those described in the earlier chapter (see my point above)**

This has been corrected in Chapters 2 and 3.

**Eye movements are removed from the EEG with EOG and ICA. I know this is standard, but given that the authors have high quality eye tracking data co-registered, wouldn't it be better to detect the eye movements using that?**

The task involved smooth-pursuit so I did not expect the eyes to be still. Therefore, I did not want to remove all the eye movements but only the eye movements associated with noise from the EEG signal. The noise is more easily isolated from within the EEG recording than from an external source.

**I'm no expert here, but why are the topographies not lined up with the outline of the head? It looks like the hotspot is outside of the skull!**

These topographical representations represent the signal at the sensor level, not as a source construction or surface projection. The hotspots are not on the outside of the skull but on the electrodes that come down the forehead and the side of the skull. As the topography is taken from above these electrodes are represented by data that appears to extend beyond the skull.

**The caption refers to 4a/b etc, I think that needs changing to reflect the correct figure number**

I have updated this in the figure caption.

**The study aims to “determine whether allocation of covert attention. . . modulated measures of overt attention”. This is one place where clear definitions are important. To me, overt attention IS eye position. And eye position isn’t changed. So what are you modulating? Sensory processing at the fovea?**

Sensory processing at the fovea would be more precise. The following sentences in the manuscript should be altered to reflect this:

The sentence:

“The current study sought to measure overt visual attention in a smooth-pursuit paradigm, and to determine whether allocation of covert attention to peripheral regions modulated measures of overt attention to a moving target. ”

Should be changed to:

“The current study sought to measure sensory processing during overt visual attention in a smooth-pursuit paradigm, and to determine whether allocation of covert attention to peripheral regions modulated measures of sensory processing during overt attention to a moving target.”

The sentence:

“The lower SSVEP power in the divided condition aligns with the view of covert and overt visual attention as expressions of a pool of attentional resources, where an increase in covert attention can lead to a concomitant reduction in overt attention (Kahneman, 1973; Lavie et al., 2004), similar in nature to the reduction in SSVEP power to foveated static stimuli observed when covert visual attention is recruited (Mishra et al., 2011).”

Should be changed to:

“The lower SSVEP power in the divided condition aligns with the view of covert and overt visual attention as expressions of a pool of attentional resources, where an increase in covert attention can lead to a concomitant reduction in sensory processing during overt attention (Kahneman, 1973; Lavie et al., 2004), similar in nature to the reduction in SSVEP power to foveated static stimuli observed when covert visual attention is recruited (Mishra et al., 2011).”

The sentence:

“Thus, our approach allowed us to investigate the fine-grained temporal modulations of overt attention resulting from allocation of covert attention, rather than the end-product.”

Should be changed to:

“Thus, our approach allowed us to investigate the fine-grained temporal modulations of sensory processing during overt attention resulting from the allocation of covert attention, rather than the end-product.”

The sentence:

“ It would therefore be more precise to suggest that we did not observe evidence of a covert shift of attention impacting overt attention in the majority of the analysis period.”

Should be changed to:

“ It would therefore be more precise to suggest that we did not observe evidence of a covert shift of attention impacting sensory processing during overt attention in the majority of the analysis period.”

The sentence:

“Such an early, discrete period of reduced overt attention may reflect a process of the encoding of spatial locations for future monitoring through covert attention, where overt attention is impacted to a lesser degree after this encoding process has occurred.”

Should be changed to:

“Such an early, discrete period of reduced sensory processing during overt attention may reflect a process of the encoding of spatial locations for future monitoring through covert attention, where sensory processing during overt attention is impacted to a lesser degree after this encoding process has occurred”

The sentence:

“ If the predictability of the time or location of potential distractor stimuli modulates the time or the strength of changes in overt visual attention during object tracking, then future studies might specifically manipulate these dimensions to de-

termine how they contribute to such effects, and whether they interact with the task requirements.”

Should be changed to:

“ If the predictability of the time or location of potential distractor stimuli modulates the time or the strength of changes in sensory processing during overt visual attention during object tracking, then future studies might specifically manipulate these dimensions to determine how they contribute to such effects, and whether they interact with the task requirements.”

The sentence:

“While our SSVEP results indicate that there was a reduction in overt attention to the moving targets when the task required a covert shift of attention to a peripheral location, this, however, does not necessarily mean that a performance decrease would also be observed had an additional behavioural task been employed.”

Should be changed to:

“While our SSVEP results indicate that there was a reduction in sensory processing during overt attention to the moving targets when the task required a covert shift of attention to a peripheral location, this, however, does not necessarily mean that a performance decrease would also be observed had an additional behavioural task been employed.”

The sentence:

“ This is in line with the perceptual load theory, which suggests that the division of visual attention across covert and overt areas is moderated by the processing load required by the tasks at hand.”

Should be changed to:

“ This is in line with the perceptual load theory, which suggests that the division of visual attention processing across covert and overt areas is moderated by the processing load required by the tasks at hand.”

The sentence:

“In these contexts, the level of overt attention may be higher than when there was no secondary task requiring visual analysis, making it more difficult (or less

likely) for covert shifts to occur.”

Should be changed to:

“In these contexts, the level of sensory processing during overt attention may be higher than when there was no secondary task requiring visual analysis, making it more difficult (or less likely) for covert shifts to occur”

The sentence:

“ It is also likely that additional visual analysis of the moving stimuli would require greater overt attention and thus may limit the amount of covert attention available for monitoring other spatial areas, as suggested by the finding that foveal distractors are harder to ignore than peripheral distractors (Beck & Lavie, 2005).”

Should be changed to:

“ It is also likely that additional visual analysis of the moving stimuli would require more sensory processing during overt attention and thus may limit the amount of covert attentional processing resources available for monitoring other spatial areas, as suggested by the finding that foveal distractors are harder to ignore than peripheral distractors (Beck & Lavie, 2005).”

The sentence:

“The nature of any such task will likely then influence the relative strength of both central overt and peripheral covert visual attention, as competition between features for visual analysis and their distractors in central vision has been found to lead to an enhancement of neural sensitivity to peripheral regions (Painter et al., 2014).”

Should be changed to:

“The nature of any such task will likely then influence the relative strength of both central overt and peripheral covert visual attention processing, as competition between features for visual analysis and their distractors in central vision has been found to lead to an enhancement of neural sensitivity to peripheral regions (Painter et al., 2014).”

The sentence:

“ Although our interpretations of this early effect is limited by these considera-

tions, we do not rule-out the possibility that overt attention may be modulated by task, even in this early time period.”

Should be changed to:

“ Although our interpretations of this early effect is limited by these considerations, we do not rule-out the possibility that sensory processing during overt attention may be modulated by task, even in this early time period.”

The sentence:

“In consideration of how low-level factors might modulate both overt and covert visual attention during smooth-pursuit, other task-related dimensions may also significantly modulate the strength of overt attention such as the speed of the moving target, and the spatial locations of where covert shifts of attention are directed.”

Should be changed to:

“In consideration of how low-level factors might modulate both overt and covert visual attention processing during smooth-pursuit, other task-related dimensions may also significantly modulate the strength of sensory processing during overt attention such as the speed of the moving target, and the spatial locations of where covert shifts of attention are directed.”

The sentence:

“The results of the current study suggested a period of reduced visual attention to a moving target when the task involved the appearance of a possible second target. However, the transience and the early timing of the effect did not suggest a sustained difference in visual attention as the appearance of a second target grew more likely, suggesting a more complex dynamic between overt visual attention and covert shifts of attention during smooth pursuit.”

Should be changed to:

“The results of the current study suggested a period of reduced visual attention processing of a moving target when the task involved the appearance of a possible second target. However, the transience and the early timing of the effect did not suggest a sustained difference in visual attention processing as the appearance of a second target grew more likely, suggesting a more complex dynamic between overt

visual attention and covert shifts of attention during smooth pursuit.”

### **D.2.2 Response to internal examiner’s comments**

**Since this publication doesn’t include a breakdown of author contributions it should be made clear what Victoria’s contributions were at the start of the chapter**

I have added this information at the start of Chapter 5.

## References

- Açık, A., Sarwary, A., Schultze-Kraft, R., Onat, S., & König, P. (2010). Developmental changes in natural viewing behavior: bottom-up and top-down differences between children, young adults and older adults. *Frontiers in Psychology, 1*, 207. doi: 10.3389/fpsyg.2010.00207
- Aguirre, G. K., Detre, J. A., Alsop, D. C., & D'Esposito, M. (1996). The parahippocampus subserves topographical learning in man. *Cerebral Cortex, 6*(6), 823–829. doi: 10.1093/cercor/6.6.823
- Aguirre, G. K., Zarahn, E., & D'esposito, M. (1998). An area within human ventral cortex sensitive to “building” stimuli: Evidence and implications. *Neuron, 21*(2), 373–383. doi: 10.1016/S0896-6273(00)80546-2
- Ales, J. M., Farzin, F., Rossion, B., & Norcia, A. M. (2012). An objective method for measuring face detection thresholds using the sweep steady-state visual evoked response. *Journal of Vision, 12*(10), 1–18. doi: 10.1167/12.10.18
- Allain, P., Nicoleau, S., Pinon, K., Etcharry-Bouyx, F., Barré, J., Berrut, G., ... Le Gall, D. (2005). Executive functioning in normal aging: A study of action planning using the zoo map test. *Brain and Cognition, 57*(1), 4–7. doi: 10.1016/j.bandc.2004.08.011
- Ampofo-Boateng, K., & Thomson, J. A. (1990). Child pedestrian accidents: A case for preventive medicine. *Health Education Research, 5*(2), 265–274. doi: 10.1093/her/5.2.265
- Ampofo-Boateng, K., & Thomson, J. A. (1991). Children's perception of safety and danger on the road. *British Journal of Psychology, 82*(4), 487–505. doi: 10.1111/j.2044-8295.1991.tb02415.x
- Anders, T. R., Fozard, J. L., & Lillyquist, T. D. (1972). Effects of age upon retrieval from short-term memory. *Developmental Psychology, 6*(2), 214–217. doi: 10.1037/h0032103
- Andersen, S., & Müller, M. (2010). Behavioral performance follows the time course of neural facilitation and suppression during cued shifts of feature-selective attention. *Proceedings of the National Academy of Sciences, 107*(31), 13878–

13882. doi: 10.1073/pnas.1002436107

- Anderson, J. A., Campbell, K. L., Amer, T., Grady, C. L., & Hasher, L. (2014). Timing is everything: Age differences in the cognitive control network are modulated by time of day. *Psychology and Aging, 29*(3), 648–657. doi: 10.1037/a0037243
- Andrea, D. J., Fildes, B. N., & Triggs, T. J. (2000). The sensitivity and bias of older driver judgements in an arrival-time task. In *Kursiust, editor proceedings of the road safety research, policing & enforcement conference*.
- Anstey, K. J., Horswill, M. S., Wood, J. M., & Hatherly, C. (2012). The role of cognitive and visual abilities as predictors in the multifactorial model of driving safety. *Accident Analysis & Prevention, 45*, 766–774. doi: 10.1016/j.aap.2011.10.006
- Baayen, H. R., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language, 59*(4), 390–412. doi: 10.1016/j.jml.2007.12.005
- Bacon, W. F., & Egeth, H. E. (1994). Overriding stimulus-driven attentional capture. *Perception & Psychophysics, 55*(5), 485–496. doi: 10.3758/BF03205306
- Ball, K. K., Beard, B. L., Roenker, D. L., Miller, R. L., & Griggs, D. S. (1988). Age and visual search: Expanding the useful field of view. *Journal of the Optical Society of America A, 5*(12), 2210–2219. doi: 10.1364/JOSAA.5.002210
- Ball, K. K., & Owsley, C. (1991). Identifying correlates of accident involvement for the older driver. *Human Factors, 33*(5), 583–595. doi: 10.1177/2F001872089103300509
- Ballard, D. H., & Hayhoe, M. M. (2009). Modelling the role of task in the control of gaze. *Visual Cognition, 17*(6-7), 1185–1204. doi: 10.1080/13506280902978477
- Bao, S., & Boyle, L. N. (2009). Age-related differences in visual scanning at median-divided highway intersections in rural areas. *Accident Analysis & Prevention, 41*(1), 146–152. doi: 10.1016/j.aap.2008.10.007
- Bar, M., & Aminoff, E. (2003). Cortical analysis of visual context. *Neuron, 38*(2), 347–358. doi: 10.1016/S0896-6273(03)00167-3

- Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, *68*(3), 255–278. doi: 10.1016/j.jml.2012.11.001
- Barton, B. K., & Morrongiello, B. A. (2011). Examining the impact of traffic environment and executive functioning on children’s pedestrian behaviors. *Developmental Psychology*, *47*(1), 182–191. doi: 10.1037/a0021308
- Barton, B. K., & Schwebel, D. C. (2007). The roles of age, gender, inhibitory control, and parental supervision in children’s pedestrian safety. *Journal of Pediatric Psychology*, *32*(5), 517–526.
- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48. doi: 10.18637/jss.v067.i01
- Becic, E., Boot, W. R., & Kramer, A. F. (2008). Training older adults to search more effectively: Scanning strategy and visual search in dynamic displays. *Psychology and Aging*, *23*(2), 461–466. doi: 10.1037/0882-7974.23.2.461
- Beck, D. M., & Lavie, N. (2005). Look here but ignore what you see: Effects of distractors at fixation. *Journal of Experimental Psychology: Human Perception and Performance*, *31*(3), 592–607. doi: 10.1037/0096-1523.31.3.592
- Beurskens, R., & Bock, O. (2012). Age-related decline of peripheral visual processing: The role of eye movements. *Experimental Brain Research*, *217*(1), 117–124. doi: 10.1007/s00221-011-2978-3
- Biassoni, F., Bina, M., Confalonieri, F., & Ciceri, R. (2018). Visual exploration of pedestrian crossings by adults and children: Comparison of strategies. *Transportation Research Part F: Traffic Psychology and Behaviour*, *56*, 227–235. doi: 10.1016/j.trf.2018.04.009
- Bieg, H.-J., Chuang, L. L., Bühlhoff, H. H., & Bresciani, J.-P. (2015). Asymmetric saccade reaction times to smooth pursuit. *Experimental Brain Research*, *233*(9), 2527–2538. doi: 10.1007/s00221-015-4323-8
- Billino, J., Bremmer, F., & Gegenfurtner, K. R. (2008). Differential aging of motion processing mechanisms: Evidence against general perceptual decline. *Vision*

*Research*, 48(10), 1254–1261. doi: 10.1016/j.visres.2008.02.014

- BITRE. (2015). Pedestrians and road safety. *Bureau of Infrastructure, Transport and Regional Economics (BITRE)*, Canberra.
- Bock, O., & Beurskens, R. (2010). Changes of locomotion in old age depend on task setting. *Gait & Posture*, 32(4), 645–649. doi: 10.1016/j.gaitpost.2010.09.009
- Bock, O., Brustio, P. R., & Borisova, S. (2015). Age-related differences of the gaze pattern in a realistic pedestrian traffic task. *International Journal of Applied Psychology*, 5(1), 13–19. doi: 10.5923/j.ijap.20150501.03
- Bock, O., & Steinberg, F. (2012). Age-related deficits of manual grasping in a laboratory versus in an everyday-like setting. *Ageing Research*, 3(1), 48–52. doi: 10.4081/ar.2012.e7
- Bock, O., & Züll, A. (2013). Characteristics of grasping movements in a laboratory and in an everyday-like context. *Human Movement Science*, 32(1), 249–256. doi: 10.1016/j.humov.2012.12.009
- Bohannon, R. W. (1997). Comfortable and maximum walking speed of adults aged 20–79 years: Reference values and determinants. *Age and Ageing*, 26(1), 15–19. doi: 10.1093/ageing/26.1.15
- Bojko, A., Kramer, A. F., & Peterson, M. S. (2004). Age equivalence in switch costs for prosaccade and antisaccade tasks. *Psychology and Aging*, 19(1), 226–234. doi: 10.1037/0882-7974.19.1.226
- Bonin-Guillaume, S., Possamaï, C.-A., Blin, O., & Hasbroucq, T. (2000). Stimulus preprocessing, response selection, and motor adjustment in the elderly: An additive factor analysis. *Cahiers de Psychologie Cognitive*, 19(2), 245–255.
- Bono, F., Oliveri, R., Zappia, M., Aguglia, U., Puccio, G., & Quattrone, A. (1996). Computerized analysis of eye movements as a function of age. *Archives of Gerontology and Geriatrics*, 22(3), 261–269. doi: 10.1016/0167-4943(96)00698-X
- Booth, J. R., Burman, D. D., Meyer, J. R., Lei, Z., Trommer, B. L., Davenport, N. D., . . . Mesulam, M. M. (2003). Neural development of selective attention and response inhibition. *NeuroImage*, 20(2), 737–751. doi: 10.1016/S1053-

- Bopp, K. L., & Verhaeghen, P. (2005). Aging and verbal memory span: A meta-analysis. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *60*(5), 223–233. doi: 10.1093/geronb/60.5.P223
- Borji, A., Sihite, D. N., & Itti, L. (2013). What stands out in a scene? A study of human explicit saliency judgment. *Vision Research*, *91*, 62–77. doi: 10.1016/j.visres.2013.07.016
- Brainard, D. H. (1997). The psychophysics toolbox. *Spatial vision*, *10*, 433–436. doi: 10.1163/156856897X00357
- Bremmer, F., Duhamel, J., Ben Hamed, S., & Graf, W. (2000). Stages of self-motion processing in primate posterior parietal cortex. *International Review of Neurobiology*, *44*, 173–198. doi: 10.1016/s0074-7742(08)60742-4
- Bremmer, F., Duhamel, J.-R., Ben Hamed, S., & Graf, W. (2002). Heading encoding in the macaque ventral intraparietal area (VIP). *European Journal of Neuroscience*, *16*(8), 1554–1568. doi: 10.1046/j.1460-9568.2002.02207.x
- Bremmer, F., Kubischik, M., Pekel, M., Lappe, M., & Hoffmann, K. (1999). Linear vestibular self-motion signals in monkey medial superior temporal area. *Annals New York Academy of Sciences*, *871*, 272–281.
- Bremmer, F., Schlack, A., Shah, N. J., Zafiris, O., Kubischik, M., Hoffmann, K.-P., ... Fink, G. R. (2001). Polymodal motion processing in posterior parietal and premotor cortex: A human fMRI study strongly implies equivalencies between humans and monkeys. *Neuron*, *29*(1), 287–296. doi: 10.1016/S0896-6273(01)00198-2
- Britten, K. H. (2008). Mechanisms of self-motion perception. *Annual Review of Neuroscience*, *31*, 389–410. doi: 10.1146/annurev.neuro.29.051605.112953
- Brodeur, D. A., & Enns, J. T. (1997). Covert visual orienting across the lifespan. *Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale*, *51*(1), 20–35. doi: 10.1037/1196-1961.51.1.20
- Bruce, N. D. B., & Tsotsos, J. (2006). Saliency based on information maximization. In *Advances in neural information processing systems* (pp. 155–162). NIPS.

- Bruce, N. D. B., & Tsotsos, J. K. (2009). Saliency, attention, and visual search: An information theoretic approach. *Journal of Vision*, *9*(3), 5–5. doi: 10.1167/9.3.5
- Bundesen, C. (1990). A theory of visual attention. *Psychological Review*, *97*(4), 523–547. doi: 10.1037/0033-295X.97.4.523
- Bunge, S. A., Dudukovic, N. M., Thomason, M. E., Vaidya, C. J., & Gabrieli, J. D. (2002). Immature frontal lobe contributions to cognitive control in children: Evidence from fMRI. *Neuron*, *33*(2), 301–311. doi: 10.1016/S0896-6273(01)00583-9
- Butler, K. M., & Zacks, R. T. (2006). Age deficits in the control of prepotent responses: Evidence for an inhibitory decline. *Psychology and Aging*, *21*(3), 638–643. doi: 10.1037/0882-7974.21.3.638
- Butler, K. M., Zacks, R. T., & Henderson, J. M. (1999). Suppression of reflexive saccades in younger and older adults: Age comparisons on an antisaccade task. *Memory & Cognition*, *27*(4), 584–591. doi: 10.3758/BF03211552
- Caird, J., & Chugh, J. (1997). The time cost of head-up displays for older drivers: Critical event onset, task location, and display type. In *Proceedings of the human factors and ergonomics society annual meeting* (Vol. 41, pp. 1008–1012). doi: 10.1177/2F107118139704100263
- Caldara, R., & Miellat, S. (2011). iMap: A novel method for statistical fixation mapping of eye movement data. *Behavior Research Methods*, *43*(3), 864–878. doi: 10.3758/s13428-011-0092-x
- Carlson, M. C., Saczynski, J. S., Rebok, G. W., Seeman, T., Glass, T. A., McGill, S., ... Fried, L. P. (2008). Exploring the effects of an “everyday” activity program on executive function and memory in older adults: Experience corps®. *The Gerontologist*, *48*(6), 793–801. doi: 10.1093/geront/48.6.793
- Carmi, R., & Itti, L. (2006). Visual causes versus correlates of attentional selection in dynamic scenes. *Vision Research*, *46*(26), 4333–4345. doi: 10.1016/j.visres.2006.08.019
- Carpenter, P. A., Just, M. A., & Shell, P. (1990). What one intelligence test mea-

- asures: A theoretical account of the processing in the raven progressive matrices test. *Psychological Review*, *97*(3), 404–431. doi: 10.1037/0033-295X.97.3.404
- Carrasco, M. (2011). Visual attention: The past 25 years. *Vision Research*, *51*(13), 1484–1525. doi: 10.1016/j.visres.2011.04.012
- Castel, A. D., Balota, D. A., Hutchison, K. A., Logan, J. M., & Yap, M. J. (2007). Spatial attention and response control in healthy younger and older adults and individuals with Alzheimer’s disease: Evidence for disproportionate selection impairments in the Simon task. *Neuropsychology*, *21*(2), 170–182. doi: 10.1037/0894-4105.21.2.170
- Castelhamo, M. S., & Heaven, C. (2011). Scene context influences without scene gist: Eye movements guided by spatial associations in visual search. *Psychonomic Bulletin & Review*, *18*(5), 890–896. doi: 10.3758/s13423-011-0107-8
- Castelhamo, M. S., & Henderson, J. M. (2007). Initial scene representations facilitate eye movement guidance in visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(4), 753–763.
- Castelhamo, M. S., & Pereira, E. J. (2018). The influence of scene context on parafoveal processing of objects. *Quarterly Journal of Experimental Psychology*, *71*(1), 229–240. doi: 10.1080/2F17470218.2017.1310263
- Cave, K. R., & Wolfe, J. M. (1990). Modeling the role of parallel processing in visual search. *Cognitive Psychology*, *22*(2), 225–271. doi: 10.1016/0010-0285(90)90017-X
- Cerella, J., & Hale, S. (1994). The rise and fall in information-processing rates over the life span. *Acta Psychologica*, *86*(2-3), 109–197. doi: 10.1016/0001-6918(94)90002-7
- Cerf, M., Frady, E. P., & Koch, C. (2009). Faces and text attract gaze independent of the task: Experimental data and computer model. *Journal of Vision*, *9*(12), 10–10. doi: 10.1167/9.12.10
- Chapman, G. J., & Hollands, M. (2006a). Age-related differences in stepping performance during step cycle-related removal of vision. *Experimental Brain Research*, *174*(4), 613–621. doi: 10.1007/s00221-006-0507-6

- Chapman, G. J., & Hollands, M. A. (2006b). Evidence for a link between changes to gaze behaviour and risk of falling in older adults during adaptive locomotion. *Gait & Posture*, *24*(3), 288–294. doi: 10.1016/j.gaitpost.2005.10.002
- Chapman, G. J., & Hollands, M. A. (2007). Evidence that older adult fallers prioritise the planning of future stepping actions over the accurate execution of ongoing steps during complex locomotor tasks. *Gait & Posture*, *26*(1), 59–67. doi: 10.1016/j.gaitpost.2006.07.010
- Chen, A., DeAngelis, G. C., & Angelaki, D. E. (2011). Representation of vestibular and visual cues to self-motion in ventral intraparietal cortex. *Journal of Neuroscience*, *31*(33), 12036–12052. doi: 10.1523/JNEUROSCI.0395-11.2011
- Chen, J., Valsecchi, M., & Gegenfurtner, K. R. (2017a). Attention is allocated closely ahead of the target during smooth pursuit eye movements: Evidence from EEG frequency tagging. *Neuropsychologia*, *102*, 206–216. doi: 10.1016/j.neuropsychologia.2017.06.024
- Chen, J., Valsecchi, M., & Gegenfurtner, K. R. (2017b). Enhanced brain responses to color during smooth-pursuit eye movements. *Journal of Neurophysiology*, *118*(2), 749–754. doi: 10.1152/jn.00208.2017
- Chen, J., Valsecchi, M., & Gegenfurtner, K. R. (2019). Saccadic suppression measured by steady-state visual evoked potentials. *Journal of Neurophysiology*, *122*(1), 251–258. doi: 10.1152/jn.00712.2018
- Chihak, B. J., Plumert, J. M., Ziemer, C. J., Babu, S., Grechkin, T., Cremer, J. F., & Kearney, J. K. (2010). Synchronizing self and object movement: How child and adult cyclists intercept moving gaps in a virtual environment. *Journal of Experimental Psychology: Human Perception and Performance*, *36*(6), 1535–1552. doi: 10.1037/a0020560
- Chrysler, S. T., Danielson, S. M., & Kirby, V. M. (1996). Age differences in visual abilities in nighttime driving field conditions. In *Proceedings of the human factors and ergonomics society annual meeting* (Vol. 40, pp. 923–927). doi: 10.1177/2F154193129604001812
- Colombo, J. (2001). The development of visual attention in infancy. *Annual Review*

- of Psychology*, 52(1), 337–367. doi: 10.1146/annurev.psych.52.1.337
- Connelly, M. L., Conaglen, H. M., Parsonson, B. S., & Isler, R. B. (1998). Child pedestrians' crossing gap thresholds. *Accident, Analysis & Prevention*, 30(4), 443–453. doi: 10.1016/S0001-4575(97)00109-7
- Cornelissen, F. W., Peters, E. M., & Palmer, J. (2002). The eyelink toolbox: Eye tracking with MATLAB and the psychophysics toolbox. *Behavior Research Methods, Instruments, & Computers*, 34(4), 613–617. doi: 10.3758/BF03195489
- Crawford, T. J., Higham, S., Mayes, J., Dale, M., Shaunak, S., & Lekwuwa, G. (2013). The role of working memory and attentional disengagement on inhibitory control: Effects of aging and Alzheimer's disease. *Age*, 35(5), 1637–1650. doi: 10.1007/s11357-012-9466-y
- Daigneault, G., Joly, P., & Frigon, J.-Y. (2002). Executive functions in the evaluation of accident risk of older drivers. *Journal of Clinical and Experimental Neuropsychology*, 24(2), 221–238. doi: 10.1076/jcen.24.2.221.993
- Daigneault, S., Braun, C. M., & Whitaker, H. A. (1992). Early effects of normal aging on perseverative and non-perseverative prefrontal measures. *Developmental Neuropsychology*, 8(1), 99–114. doi: 10.1080/87565649209540518
- De Brouwer, S., Yuksel, D., Blohm, G., Missal, M., & Lefèvre, P. (2002). What triggers catch-up saccades during visual tracking? *Journal of Neurophysiology*, 87(3), 1646–1650. doi: 10.1152/jn.00432.2001
- de Lissa, P., Caldara, R., Nicholls, V., & Miellet, S. (2020, 08). In pursuit of visual attention: SSVEP frequency-tagging moving targets. *PLOS ONE*, 15(8), 1–15. Retrieved from <https://doi.org/10.1371/journal.pone.0236967>
- Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, 134(1), 9–21. doi: 10.1016/j.jneumeth.2003.10.009
- Department for Transport. (2012). *Setting local speed limits*. Department for Transport. London.
- Department for Transport. (2020). *Lesson 1: Do you stop, look, listen, think?*

<https://www.think.gov.uk/resource/lesson-1-do-you-stop-look-listen-think/>.

(Accessed: 2020-04-22)

- D'Errico, J. (2010). *arclength*. MATLAB Central File Exchange. Retrieved from <https://uk.mathworks.com/matlabcentral/fileexchange/34871-arclength> (1.0)
- Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*, 135–168. doi: 10.1146/annurev-psych-113011-143750
- Dienes, Z. (2011). Bayesian versus orthodox statistics: Which side are you on? *Perspectives on Psychological Science*, *6*(3), 274–290. doi: 10.1177/2F1745691611406920
- Di Fabio, R. P., Greany, J. F., & Zampieri, C. (2003). Saccade-stepping interactions revise the motor plan for obstacle avoidance. *Journal of Motor Behavior*, *35*(4), 383–397. doi: 10.1080/00222890309603158
- Di Fabio, R. P., Zampieri, C., Henke, J., Olson, K., Rickheim, D., & Russell, M. (2005). Influence of elderly executive cognitive function on attention in the lower visual field during step initiation. *Gerontology*, *51*(2), 94–107. doi: 10.1159/000082194
- Dommes, A., Cavallo, V., Dubuisson, J.-B., Tournier, I., & Vienne, F. (2014). Crossing a two-way street: Comparison of young and old pedestrians. *Journal of Safety Research*, *50*, 27–34. doi: 10.1016/j.jsr.2014.03.008
- Dommes, A., Cavallo, V., & Oxley, J. A. (2013). Functional declines as predictors of risky street-crossing decisions in older pedestrians. *Accident Analysis & Prevention*, *59*, 135–143. doi: 10.1016/j.aap.2013.05.017
- Dowiasch, S., Marx, S., Einhäuser, W., & Bremmer, F. (2015). Effects of aging on eye movements in the real world. *Frontiers in Human Neuroscience*, *9*, 46. doi: 10.3389/fnhum.2015.00046
- Duffy, C. J., & Wurtz, R. H. (1991). Sensitivity of MST neurons to optic flow stimuli. I. A continuum of response selectivity to large-field stimuli. *Journal of Neurophysiology*, *65*(6), 1329–1345. doi: 10.1152/jn.1991.65.6.1329
- Dumontheil, I. (2014). Development of abstract thinking during childhood and ado-

- lescence: The role of rostrolateral prefrontal cortex. *Developmental Cognitive Neuroscience*, *10*, 57–76. doi: 10.1016/j.dcn.2014.07.009
- Dumontheil, I., Burgess, P. W., & Blakemore, S.-J. (2008). Development of rostral prefrontal cortex and cognitive and behavioural disorders. *Developmental Medicine & Child Neurology*, *50*(3), 168–181. doi: 10.1111/j.1469-8749.2008.02026.x
- Dunbar, G., Hill, R., & Lewis, V. (2001). Children's attentional skills and road behavior. *Journal of Experimental Psychology: Applied*, *7*(3), 227–234. doi: 10.1037/1076-898X.7.3.227
- Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, *96*(3), 433–458.
- Durston, S., Thomas, K. M., Yang, Y., Uluğ, A. M., Zimmerman, R. D., & Casey, B. (2002). A neural basis for the development of inhibitory control. *Developmental Science*, *5*(4), 9–16. doi: 10.1111/1467-7687.00235
- Dye, M. W., & Bavelier, D. (2010). Differential development of visual attention skills in school-age children. *Vision Res.*, *50*(4), 452–459. doi: 10.1016/j.visres.2009.10.010
- Eckstein, M. P., Drescher, B. A., & Shimozaki, S. S. (2006). Attentional cues in real scenes, saccadic targeting, and Bayesian priors. *Psychological Science*, *17*(11), 973–980. doi: 10.1111/2Fj.1467-9280.2006.01815.x
- Egan, C. D. (2012). *Children's gaze behaviour at real-world and simulated road crossings* (Unpublished doctoral dissertation). Edinburgh Napier University.
- Einhäuser, W., Spain, M., & Perona, P. (2008). Objects predict fixations better than early saliency. *Journal of Vision*, *8*(14), 18–18. doi: 10.1167/8.14.18
- Enns, J. T. (1990). Relations between components of visual attention. In *Advances in psychology* (Vol. 69, pp. 139–158). Elsevier. doi: 10.1016/S0166-4115(08)60454-9
- Enns, J. T., & Brodeur, D. A. (1989). A developmental study of covert orienting to peripheral visual cues. *Journal of Experimental Child Psychology*, *48*(2), 171–189. doi: 10.1016/0022-0965(89)90001-5

- Epelboim, J., Steinman, R. M., Kowler, E., Edwards, M., Pizlo, Z., Erkelens, C. J., & Collewijn, H. (1995). The function of visual search and memory in sequential looking tasks. *Vision Research*, *35*(23-24), 3401–3422. doi: 10.1016/0042-6989(95)00080-X
- Eppinger, B., Kray, J., Mecklinger, A., & John, O. (2007). Age differences in task switching and response monitoring: Evidence from ERPs. *Biological Psychology*, *75*(1), 52–67. doi: 10.1016/j.biopsycho.2006.12.001
- Epstein, R., & Kanwisher, N. (1998). A cortical representation of the local visual environment. *Nature*, *392*(6676), 598–601. doi: 10.1038/33402
- Eriksen, C. W., & Hoffman, J. E. (1972). Temporal and spatial characteristics of selective encoding from visual displays. *Perception & Psychophysics*, *12*(2), 201–204.
- ERSO. (2018). *Traffic safety basic facts on pedestrians*. European Commission, Directorate General for Transport.
- Esteban-Cornejo, I., Carlson, J. A., Conway, T. L., Cain, K. L., Saelens, B. E., Frank, L. D., . . . Sallis, J. F. (2016). Parental and adolescent perceptions of neighborhood safety related to adolescents' physical activity in their neighborhood. *Research Quarterly for Exercise and Sport*, *87*(2), 191–199. doi: 10.1080/02701367.2016.1153779
- Faust, M. E., & Balota, D. A. (1997). Inhibition of return and visuospatial attention in healthy older adults and individuals with dementia of the Alzheimer type. *Neuropsychology*, *11*(1), 13–29. doi: 10.1037/0894-4105.11.1.13
- Fehd, H. M., & Seiffert, A. E. (2010). Looking at the center of the targets helps multiple object tracking. *Journal of Vision*, *10*(4), 1–13. doi: 10.1167/10.4.19
- Fisk, J. E., & Warr, P. B. (1998). Associative learning and short-term forgetting as a function of age, perceptual speed, and central executive functioning. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *53*(2), 112–121. doi: 10.1093/geronb/53B.2.P112
- Fjell, A. M., McEvoy, L., Holland, D., Dale, A. M., & Walhovd, K. B. (2013). Brain changes in older adults at very low risk for Alzheimer's disease. *Journal of*

- Neuroscience*, 33(19), 8237–8242. doi: 10.1523/JNEUROSCI.5506-12.2013
- Fjell, A. M., Sneve, M. H., Grydeland, H., Storsve, A. B., & Walhovd, K. B. (2017). The disconnected brain and executive function decline in aging. *Cerebral Cortex*, 27(3), 2303–2317. doi: 10.1093/cercor/bhw082
- Foot, H., Tolmie, A., Thomson, J. A., McLaren, B., & Whelan, K. (1999). Recognizing the hazards. *The Psychologist*, 12(8), 400–402.
- Foulsham, T., & Underwood, G. (2007). How does the purpose of inspection influence the potency of visual salience in scene perception? *Perception*, 36(8), 1123–1138. doi: 10.1068/2Fp5659
- Foulsham, T., & Underwood, G. (2008). What can saliency models predict about eye movements? Spatial and sequential aspects of fixations during encoding and recognition. *Journal of Vision*, 8(2), 6–6. doi: 10.1167/8.2.6
- Foulsham, T., Walker, E., & Kingstone, A. (2011). The where, what and when of gaze allocation in the lab and the natural environment. *Vision Research*, 51(17), 1920–1931. doi: 10.1016/j.visres.2011.07.002
- Fozard, J. L., & Gordon-Salant, S. (2001). Changes in vision and hearing with aging. In J. E. Birren & K. W. E. Schaie (Eds.), *Handbook of the psychology of aging* (pp. 241–266). Academic Press.
- Franchak, J. M., & Adolph, K. E. (2010). Visually guided navigation: Head-mounted eye-tracking of natural locomotion in children and adults. *Vision Research*, 50(24), 2766–2774. doi: 10.1016/j.visres.2010.09.024
- Friedman, B. H., & Thayer, J. F. (1991). Facial muscle activity and EEG recordings: Redundancy analysis. *Electroencephalography and Clinical Neurophysiology*, 79(5), 358–360. doi: 10.1016/0013-4694(91)90200-N
- Friedman, D., Nessler, D., Johnson Jr, R., Ritter, W., & Bersick, M. (2007). Age-related changes in executive function: An event-related potential (ERP) investigation of task-switching. *Aging, Neuropsychology, and Cognition*, 15(1), 95–128. doi: 10.1080/13825580701533769
- Friston, K., Adams, R., Perrinet, L., & Breakspear, M. (2012). Perceptions as hypotheses: Saccades as experiments. *Frontiers in Psychology*, 3, 151. doi:

- Fukushima, J., Hatta, T., & Fukushima, K. (2000). Development of voluntary control of saccadic eye movements: I. Age-related changes in normal children. *Brain and Development*, *22*(3), 173–180. doi: 10.1016/S0387-7604(00)00101-7
- Gazzaley, A., & D'esposito, M. (2007). Top-down modulation and normal aging. *Annals of the New York Academy of Sciences*, *1097*(1), 67–83. doi: 10.1196/annals.1379.010
- Geraghty, J., Holland, C., & Rochelle, K. (2016). Examining links between cognitive markers, movement initiation and change, and pedestrian safety in older adults. *Accident Analysis & Prevention*, *89*, 151–159. doi: 10.1016/j.aap.2015.12.019
- Gielen, A. C., De Francesco, S., Bishai, D., Mahoney, P., Ho, S., & Guyer, B. (2004). Child pedestrians: The role of parental beliefs and practices in promoting safe walking in urban neighborhoods. *Journal of Urban Health*, *81*(4), 545–555. doi: 10.1093/jurban/jth139
- Gillam, B. (1992). The status of perceptual grouping 70 years after Wertheimer. *Australian Journal of Psychology*, *44*(3), 157–162. doi: 10.1080/00049539208259836
- Goldberg, M. C., Maurer, D., & Lewis, T. L. (2001). Developmental changes in attention: The effects of endogenous cueing and of distractors. *Developmental Science*, *4*(2), 209–219. doi: 10.1111/1467-7687.00166
- Goncharova, I. I., McFarland, D. J., Vaughan, T. M., & Wolpaw, J. R. (2003). EMG contamination of EEG: Spectral and topographical characteristics. *Clinical Neurophysiology*, *114*(9), 1580–1593. doi: 10.1016/S1388-2457(03)00093-2
- Grechkin, T. Y., Chihak, B. J., Cremer, J. F., Kearney, J. K., & Plumert, J. M. (2013). Perceiving and acting on complex affordances: How children and adults bicycle across two lanes of opposing traffic. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(1), 23–36. doi: 10.1037/a0029716

- Greenwood, P. M., Parasuraman, R., & Haxby, J. V. (1993). Changes in visuospatial attention over the adult lifespan. *Neuropsychologia*, *31*(5), 471–485. doi: 10.1016/0028-3932(93)90061-4
- Grgič, R. G., Calore, E., & de'Sperati, C. (2016). Covert enaction at work: Recording the continuous movements of visuospatial attention to visible or imagined targets by means of steady-state visual evoked potentials (SSVEPs). *Cortex*, *74*, 31–52. doi: 10.1016/j.cortex.2015.10.008
- Grill-Spector, K. (2003). The neural basis of object perception. *Current Opinion in Neurobiology*, *13*(2), 159–166. doi: 10.1016/S0959-4388(03)00040-0
- Gu, Y., Angelaki, D. E., & DeAngelis, G. C. (2008). Neural correlates of multisensory cue integration in macaque MSTd. *Nature Neuroscience*, *11*(10), 1201–1210. doi: 10.1038/nm.2191
- Hampshire, A., Gruszka, A., Fallon, S. J., & Owen, A. M. (2008). Inefficiency in self-organized attentional switching in the normal aging population is associated with decreased activity in the ventrolateral prefrontal cortex. *Journal of Cognitive Neuroscience*, *20*(9), 1670–1686. doi: 10.1162/jocn.2008.20115
- Harsay, H. A., Buitenweg, J. I., Wijnen, J. G., Guerreiro, M. J., & Ridderinkhof, K. R. (2010). Remedial effects of motivational incentive on declining cognitive control in healthy aging and Parkinson's disease. *Frontiers in Aging Neuroscience*, *2*, 144. doi: 10.3389/fnagi.2010.00144
- Hart, R. P., & Bean, M. K. (2010). Executive function, intellectual decline and daily living skills. *Aging, Neuropsychology, and Cognition*, *18*(1), 64–85. doi: 10.1080/13825585.2010.510637
- Hartley, A. A., Kieley, J., & McKenzie, C. R. (1992). Allocation of visual attention in younger and older adults. *Attention, Perception, & Psychophysics*, *52*(2), 175–185. doi: 10.3758/BF03206771
- Hartley, A. A., & McKenzie, C. R. (1991). Attentional and perceptual contributions to the identification of extrafoveal stimuli: Adult age comparisons. *Journal of Gerontology*, *46*(5), 202–206. doi: 10.1093/geronj/46.5.P202
- Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging:

- A review and a new view. *The Psychology of Learning and Motivation*, 22, 193–225. doi: 10.1016/S0079-7421(08)60041-9
- Hasson, U., Harel, M., Levy, I., & Malach, R. (2003). Large-scale mirror-symmetry organization of human occipito-temporal object areas. *Neuron*, 37(6), 1027–1041. doi: 10.1016/S0896-6273(03)00144-2
- Hayes, T. R., & Henderson, J. M. (2017). Scan patterns during real-world scene viewing predict individual differences in cognitive capacity. *Journal of Vision*, 17(5), 23–23. doi: 10.1167/17.5.23
- Hayhoe, M. M., Shrivastava, A., Mruczek, R., & Pelz, J. B. (2003). Visual memory and motor planning in a natural task. *Journal of Vision*, 3(1), 6–6. doi: 10.1167/3.1.6
- Heinen, S. J., Jin, Z., & Watamaniuk, S. N. (2011). Flexibility of foveal attention during ocular pursuit. *Journal of Vision*, 9(2), 1–12. doi: 10.1167/11.2.9
- Henderson, J. M. (2017). Gaze control as prediction. *Trends in Cognitive Sciences*, 21(1), 15–23. doi: 10.1016/j.tics.2016.11.003
- Henderson, J. M., Brockmole, J. R., Castelhana, M. S., & Mack, M. (2007). Visual saliency does not account for eye movements during visual search in real-world scenes. In *Eye movements* (pp. 537–562). Elsevier. doi: 10.1016/B978-008044980-7/50027-6
- Henderson, J. M., Chanceaux, M., & Smith, T. J. (2009). The influence of clutter on real-world scene search: Evidence from search efficiency and eye movements. *Journal of Vision*, 9(1), 32–32. doi: 10.1167/9.1.32
- Henderson, J. M., Malcolm, G. L., & Schandl, C. (2009). Searching in the dark: Cognitive relevance drives attention in real-world scenes. *Psychonomic Bulletin & Review*, 16(5), 850–856. doi: 10.3758/PBR.16.5.850
- Henderson, J. M., Weeks Jr, P. A., & Hollingworth, A. (1999). The effects of semantic consistency on eye movements during complex scene viewing. *Journal of Experimental Psychology: Human Perception and Performance*, 25(1), 210–228. doi: 10.1037/0096-1523.25.1.210
- Hill, R., Lewis, V., & Dunbar, G. (2000). Young children's concepts of dan-

- ger. *British Journal of Developmental Psychology*, *18*(1), 103–119. doi: 10.1348/026151000165607
- Hilton, C., Miellet, S., Slattery, T. J., & Wiener, J. (2019). Are age-related deficits in route learning related to control of visual attention? *Psychological Research*, 1–12. doi: 10.1007/s00426-019-01159-5
- Hirsiger, S., Koppelmans, V., Mérillat, S., Erdin, C., Narkhede, A., Brickman, A. M., & Jäncke, L. (2017). Executive functions in healthy older adults are differentially related to macro-and microstructural white matter characteristics of the cerebral lobes. *Frontiers in Aging Neuroscience*, *9*, 373. doi: 10.3389/fnagi.2017.00373
- Ho, G., Scialfa, C. T., Caird, J. K., & Graw, T. (2001). Visual search for traffic signs: The effects of clutter, luminance, and aging. *Human Factors*, *43*(2), 194–207. doi: 10.1518/2F001872001775900922
- Holmberg, N., Holmqvist, K., & Sandberg, H. (2015). Children’s attention to online adverts is related to low-level saliency factors and individual level of gaze control. *Journal of Eye Movement Research*, *8*(2), 1–10. doi: 10.16910/jemr.8.2.2
- Hooper, C. J., Luciana, M., Conklin, H. M., & Yarger, R. S. (2004). Adolescents’ performance on the Iowa Gambling Task: Implications for the development of decision making and ventromedial prefrontal cortex. *Developmental Psychology*, *40*(6), 1148–1158. doi: 10.1037/0012-1649.40.6.1148
- Hsieh, S., & Fang, W. (2012). Elderly adults through compensatory responses can be just as capable as young adults in inhibiting the Flanker influence. *Biological Psychology*, *90*(2), 113–126. doi: 10.1016/j.biopsycho.2012.03.006
- Hunt, M., Harper, D. N., & Lie, C. (2011). Mind the gap: Training road users to use speed and distance when making gap-acceptance decisions. *Accident Analysis & Prevention*, *43*(6), 2015–2023. doi: 10.1016/j.aap.2011.05.020
- Hutton, S., & Tegally, D. (2005). The effects of dividing attention on smooth pursuit eye tracking. *Experimental Brain Research*, *163*(3), 306–313. doi: 10.1007/s00221-004-2171-z
- Hwang, A. D., Wang, H.-C., & Pomplun, M. (2011). Semantic guidance of eye

- movements in real-world scenes. *Vision Research*, *51*(10), 1192–1205. doi: 10.1016/j.visres.2011.03.010
- Hwang, K., Ghuman, A. S., Manoach, D. S., Jones, S. R., & Luna, B. (2016). Frontal preparatory neural oscillations associated with cognitive control: A developmental study comparing young adults and adolescents. *NeuroImage*, *136*, 139–148. doi: 10.1016/j.neuroimage.2016.05.017
- Hwang, K., Velanova, K., & Luna, B. (2010). Strengthening of top-down frontal cognitive control networks underlying the development of inhibitory control: A functional magnetic resonance imaging effective connectivity study. *Journal of Neuroscience*, *30*(46), 15535–15545. doi: 10.1523/JNEUROSCI.2825-10.2010
- Irving, E. L., Tajik-Parvinchi, D. J., Lillakas, L., González, E. G., & Steinbach, M. J. (2009). Mixed pro and antisaccade performance in children and adults. *Brain Research*, *1255*, 67–74. doi: 10.1016/j.brainres.2008.12.006
- Irwin-Chase, H., & Burns, B. (2000). Developmental changes in children’s abilities to share and allocate attention in a dual task. *Journal of Experimental Child Psychology*, *77*(1), 61–85. doi: 10.1006/jecp.1999.2557
- Ishai, A., Ungerleider, L. G., Martin, A., Schouten, J. L., & Haxby, J. V. (1999). Distributed representation of objects in the human ventral visual pathway. *Proceedings of the National Academy of Sciences*, *96*(16), 9379–9384. doi: 10.1073/pnas.96.16.9379
- Itti, L., & Koch, C. (2000). A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision Research*, *40*(10-12), 1489–1506. doi: 10.1016/S0042-6989(99)00163-7
- Itti, L., & Koch, C. (2001). Computational modelling of visual attention. *Nature Reviews Neuroscience*, *2*(3), 194–203. doi: 10.1038/35058500
- JASP Team. (2019). *Jasp*. Retrieved from <https://hadoop.apache.org>
- Jiang, P., Tokariev, M., Aronen, E. T., Salonen, O., Ma, Y., Vuontela, V., & Carlson, S. (2014). Responsiveness and functional connectivity of the scene-sensitive retrosplenial complex in 7–11-year-old children. *Brain and Cognition*, *92*, 61–72. doi: 10.1016/j.bandc.2014.10.005

- Jin, Z., Reeves, A., Watamaniuk, S. N. J., & Heinen, S. J. (2013). Shared attention for smooth pursuit and saccades. *Journal of Vision, 13*(4), 7. doi: 10.1167/13.4.7
- Juncos-Rabadán, O., Pereiro, A. X., & Facal, D. (2008). Cognitive interference and aging: Insights from a spatial stimulus–response consistency task. *Acta Psychologica, 127*(2), 237–246. doi: 10.1016/j.actpsy.2007.05.003
- Kahneman, D. (1973). *Attention and effort* (Vol. 1063). Prentice-Hall.
- Kastner, S., & Ungerleider, L. G. (2000). Mechanisms of visual attention in the human cortex. *Annual Review of Neuroscience, 23*(1), 315–341. doi: 10.1146/annurev.neuro.23.1.315
- Keall, M. D. (1995). Pedestrian exposure to risk of road accident in New Zealand. *Accident Analysis & Prevention, 27*(5), 729–740. doi: 10.1016/0001-4575(95)00019-V
- Kell, D. B., & Oliver, S. G. (2004). Here is the evidence, now what is the hypothesis? The complementary roles of inductive and hypothesis-driven science in the post-genomic era. *Bioessays, 26*(1), 99–105. doi: 10.1002/bies.10385
- Khan, A. Z., Lefèvre, P., Heinen, S. J., & Blohm, G. (2010). The default allocation of attention is broadly ahead of smooth pursuit. *Journal of Vision, 10*(13), 1–17. doi: 10.1167/10.13.7
- Kidder, D. P., Park, D. C., Hertzog, C., & Morrell, R. W. (1997). Prospective memory and aging: The effects of working memory and prospective memory task load. *Aging, Neuropsychology, and Cognition, 4*(2), 93–112. doi: 10.1080/13825589708256639
- Kim, M.-S., & Cave, K. R. (1999). Top-down and bottom-up attentional control: On the nature of interference from a salient distractor. *Attention, Perception & Psychophysics, 61*(6), 1009–1023. doi: 10.3758/BF03207609
- Kim, Y. J., Grabowecky, M., Paller, K. A., Muthu, K., & Suzuki, S. (2007). Attention induces synchronization-based response gain in steady-state visual evoked potentials. *Nature Neuroscience, 10*(1), 117–125.
- Kingdom, M. U. (2017). *Detecting cars using gaussian mix-*

- ture models – matlab and simulink example. Retrieved from <https://uk.mathworks.com/help/vision/examples/detecting-cars-using-gaussian-mixture-models.htmlresponsiveoffcanvas> (1.0)
- Kingdom, M. U. (2019). *Using kalman filter for object tracking*. Retrieved from <https://uk.mathworks.com/help/vision/examples/using-kalman-filter-for-object-tracking.html>
- Kingstone, A., Smilek, D., & Eastwood, J. D. (2008). Cognitive ethology: A new approach for studying human cognition. *British Journal of Psychology, 99*(3), 317–340. doi: 10.1348/000712607X251243
- Klein, C., Fischer, B., Hartnegg, K., Heiss, W., & Roth, M. (2000). Optomotor and neuropsychological performance in old age. *Experimental Brain Research, 135*(2), 141–154. doi: 10.1007/s002210000506
- Klein, C., & Foerster, F. (2001). Development of prosaccade and antisaccade task performance in participants aged 6 to 26 years. *Psychophysiology, 38*(2), 179–189. doi: 10.1111/1469-8986.3820179
- Kline, D. W., Kline, T. J., Fozard, J. L., Kosnik, W., Schieber, F., & Sekuler, R. (1992). Vision, aging, and driving: The problems of older drivers. *Journal of Gerontology, 47*(1), 27–34. doi: 10.1093/geronj/47.1.P27
- Koch, C., & Ullman, S. (1985). Shifts in selective visual attention: Towards the underlying neural circuitry. *Human Neurobiology, 4*, 219–227. doi: 10.1007/978-94-009-3833-5\_5
- Komogortsev, O. V., & Karpov, A. (2013). Automated classification and scoring of smooth pursuit eye movements in the presence of fixations and saccades. *Behavior Research Methods, 45*(1), 203–215. doi: 10.3758/s13428-012-0234-9
- Konrad, K., Neufang, S., Thiel, C. M., Specht, K., Hanisch, C., Fan, J., ... Fink, G. R. (2005). Development of attentional networks: An fMRI study with children and adults. *NeuroImage, 28*(2), 429–439. doi: 10.1016/j.neuroimage.2005.06.065
- Kriegeskorte, N., Simmons, W. K., Bellgowan, P. S. F., & Baker, C. I. (2009).

- Circular analysis in systems neuroscience: The dangers of double dipping. *Nature Neuroscience*, *12*(5), 535–540. doi: 10.1038/nn.2303
- Kubo-Kawai, N., & Kawai, N. (2010). Elimination of the enhanced Simon effect for older adults in a three-choice situation: Ageing and the Simon effect in a go/no-go Simon task. *The Quarterly Journal of Experimental Psychology*, *63*(3), 452–464. doi: 10.1080/2F17470210902990829
- Kuhn, G., & Teszka, R. (2017). Don't get misdirected! Differences in overt and covert attentional inhibition between children and adults. *The Quarterly Journal of Experimental Psychology*, *71*(3), 688–694. doi: 10.1080/2F17470218.2016.1277770
- Kuhn, G., Teszka, R., Tenaw, N., & Kingstone, A. (2016). Don't be fooled! Attentional responses to social cues in a face-to-face and video magic trick reveals greater top-down control for overt than covert attention. *Cognition*, *146*, 136–142. doi: 10.1016/j.cognition.2015.08.005
- Land, M. F., & Furneaux, S. (1997). The knowledge base of the oculomotor system. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *352*(1358), 1231–1239. doi: 10.1098/rstb.1997.0105
- Land, M. F., & McLeod, P. (2000). From eye movements to actions: How batsmen hit the ball. *Nature Neuroscience*, *3*(12), 1340–1345. doi: 10.1038/81887
- Land, M. F., Mennie, N., & Rusted, J. (1999). The roles of vision and eye movements in the control of activities of daily living. *Perception*, *28*(11), 1311–1328. doi: 10.1068/2Fp2935
- Lao, J., Miellet, S., Pernet, C. R., Sokhn, N., & Caldara, R. (2017). iMap4: An open source toolbox for the statistical fixation mapping of eye movement data with linear mixed modeling. *Behavior Research Methods*, *49*(2), 559–575. doi: 10.3758/s13428-016-0737-x
- Lappin, J. S., Morse, D. L., & Seiffert, A. E. (2016). The channel capacity of visual awareness divided among multiple moving objects. *Attention, Perception, & Psychophysics*, *78*(8), 2469–2493. doi: 10.3758/s13414-016-1162-z
- Larsson, L., Nyström, M., Andersson, R., & Stridh, M. (2015). Detection of fixations

- and smooth pursuit movements in high-speed eye-tracking data. *Biomedical Signal Processing and Control*, *18*, 145–152. doi: 10.1016/j.bspc.2014.12.008
- Larsson, L., Nyström, M., Ardö, H., Åström, K., & Stridh, M. (2016). Smooth pursuit detection in binocular eye-tracking data with automatic video-based performance evaluation. *Journal of Vision*, *16*(15), 20–20. doi: 10.1167/16.15.20
- Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(3), 451–468. doi: 10.1037/0096-1523.21.3.451
- Lavie, N. (2005). Distracted and confused?: Selective attention under load. *Trends in Cognitive Sciences*, *9*(2), 75–82. doi: 10.1016/j.tics.2004.12.004
- Lavie, N. (2010). Attention, distraction, and cognitive control under load. *Current Directions in Psychological Science*, *19*(3), 143–148. doi: 10.1177/2F0963721410370295
- Lavie, N., Hirst, A., De Fockert, J. W., & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General*, *133*(3), 339–354.
- Lavie, N., & Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Perception & Psychophysics*, *56*(2), 183–197. doi: 10.3758/BF03213897
- Leclercq, V., & Siéroff, E. (2013). Development of endogenous orienting of attention in school-age children. *Child Neuropsychology*, *19*(4), 400–419. doi: 10.1080/09297049.2012.682568
- Lee, D. N., Young, D. S., & McLaughlin, C. M. (1984). A roadside simulation of road crossing for children. *Ergonomics*, *27*(12), 1271–1281. doi: 10.1080/00140138408963608
- Lee Salvatierra, J., & Rosselli, M. (2011). The effect of bilingualism and age on inhibitory control. *International Journal of Bilingualism*, *15*(1), 26–37. doi: 10.1177/2F1367006910371021
- Legrand, A., Mazars, K. D., Lemoine, C., Nougier, V., & Olivier, I. (2016). Interference between oculomotor and postural tasks in 7–8-year-old children and

- adults. *Experimental Brain Research*, *234*(6), 1667–1677. doi: 10.1007/s00221-016-4565-0
- Leshikar, E. D., Gutchess, A. H., Hebrank, A. C., Sutton, B. P., & Park, D. C. (2010). The impact of increased relational encoding demands on frontal and hippocampal function in older adults. *Cortex*, *46*(4), 507–521. doi: 10.1016/j.cortex.2009.07.011
- Lien, M.-C., Gemperle, A., & Ruthruff, E. (2011). Aging and involuntary attention capture: Electrophysiological evidence for preserved attentional control with advanced age. *Psychology and Aging*, *26*(1), 188–202. doi: 10.1037/a0021073
- Limbourg, M., & Gerber, D. (1981). A parent training program for the road safety education of preschool children. *Accident Analysis & Prevention*, *13*(3), 255–267. doi: 10.1016/0001-4575(81)90008-7
- Lindh, D., Sligte, I. G., Asseondi, S., Shapiro, K. L., & Charest, I. (2019). Conscious perception of natural images is constrained by category-related visual features. *Nature Communications*, *10*(1), 1–9. doi: 10.1038/s41467-019-12135-3
- Lobjois, R., & Cavallo, V. (2007). Age-related differences in street-crossing decisions: The effects of vehicle speed and time constraints on gap selection in an estimation task. *Accident Analysis & Prevention*, *39*(5), 934–943. doi: 10.1016/j.aap.2006.12.013
- Loftus, G. R., & Mackworth, N. H. (1978). Cognitive determinants of fixation location during picture viewing. *Journal of Experimental Psychology: Human Perception and Performance*, *4*(4), 565–572. doi: 10.1037/0096-1523.4.4.565
- Lovejoy, L. P., Fowler, G. A., & Krauzlis, R. J. (2009). Spatial allocation of attention during smooth pursuit eye movements. *Vision Research*, *49*(10), 1275–1285. doi: 10.1016/j.visres.2009.01.011
- Luciana, M., Conklin, H. M., Hooper, C. J., & Yarger, R. S. (2005). The development of nonverbal working memory and executive control processes in adolescents. *Child Development*, *76*(3), 697–712. doi: 10.1111/j.1467-8624.2005.00872.x
- Ludwig, C. J., Davies, J. R., & Eckstein, M. P. (2014). Foveal analysis and peripheral selection during active visual sampling. *Proceedings of the National Academy*

- of Sciences*, 111(2), 291–299. doi: 10.1073/pnas.1313553111
- Luis, C. A., Keegan, A. P., & Mullan, M. (2009). Cross validation of the Montreal Cognitive Assessment in community dwelling older adults residing in the Southeastern US. *International Journal of Geriatric Psychiatry*, 24(2), 197–201. doi: 10.1002/gps.2101
- Luna, B., & Sweeney, J. A. (2004). The emergence of collaborative brain function: FMRI studies of the development of response inhibition. *Annals of the New York Academy of Sciences*, 1021(1), 296–309. doi: 10.1196/annals.1308.035
- Lustig, C., & Jantz, T. (2015). Questions of age differences in interference control: When and how, not if? *Brain Research*, 1612, 59–69. doi: 10.1016/j.brainres.2014.10.024
- Luszcz, M. (2011). Executive function and cognitive aging. In *Handbook of the psychology of aging* (pp. 59–72). Elsevier. doi: 10.1016/B978-0-12-380882-0.00004-8
- Mackworth, N. H. (1965). Visual noise causes tunnel vision. *Psychonomic Science*, 3(1-12), 67–68. doi: 10.3758/BF03343023
- Macpherson, A., Roberts, I., & Pless, I. B. (1998). Children's exposure to traffic and pedestrian injuries. *American Journal of Public Health*, 88(12), 1840–1843. doi: 10.2105/AJPH.88.12.1840
- Madden, D. J., Spaniol, J., Whiting, W. L., Bucur, B., Provenzale, J. M., Cabeza, R., ... Huettel, S. A. (2007). Adult age differences in the functional neuroanatomy of visual attention: A combined fMRI and DTI study. *Neurobiology of Aging*, 28(3), 459–476. doi: 10.1016/j.neurobiolaging.2006.01.005
- Madden, D. J., Whiting, W. L., & Huettel, S. A. (2005). Age-related changes in neural activity during visual perception and attention. *Cognitive Neuroscience of Aging: Linking Cognitive and Cerebral Aging*, 157–185.
- Madden, D. J., Whiting, W. L., Provenzale, J. M., & Huettel, S. A. (2004). Age-related changes in neural activity during visual target detection measured by fMRI. *Cerebral Cortex*, 14(2), 143–155. doi: 10.1093/cercor/bhg113
- Maguire, E. (2001). The retrosplenial contribution to human navigation: A review of

- lesion and neuroimaging findings. *Scandinavian Journal of Psychology*, *42*(3), 225–238. doi: 10.1111/1467-9450.00233
- Mair, P., & Wilcox, R. (2018). WRS2: Wilcox robust estimation and testing [Computer software manual]. Retrieved from <http://CRAN.R-project.org/package=WRS2> (0.10-0)
- Malcolm, G. L., & Henderson, J. M. (2010). Combining top-down processes to guide eye movements during real-world scene search. *Journal of Vision*, *10*(2), 4–4. doi: 10.1167/10.2.4
- Maldonado, T., Orr, J. M., Goen, J. R., & Bernard, J. A. (2020). Age differences in the subcomponents of executive functioning. *The Journals of Gerontology: Series B*. doi: 10.1093/geronb/gbaa005
- Maltz, M., & Shinar, D. (1999). Eye movements of younger and older drivers. *Human Factors*, *41*(1), 15–25. doi: 10.1518/2F001872099779577282
- Marat, S., Phuoc, T. H., Granjon, L., Guyader, N., Pellerin, D., & Guérin-Dugué, A. (2009). Modelling spatio-temporal saliency to predict gaze direction for short videos. *International Journal of Computer Vision*, *82*(3), 231–243. doi: 10.1007/s11263-009-0215-3
- Martin, S. L., Lee, S. M., & Lowry, R. (2007). National prevalence and correlates of walking and bicycling to school. *American Journal of Preventive Medicine*, *33*(2), 98–105. doi: 10.1016/j.amepre.2007.04.024
- Maruta, J., Suh, M., Niogi, S. N., Mukherjee, P., & Ghajar, J. (2010). Visual tracking synchronization as a metric for concussion screening. *The Journal of Head Trauma Rehabilitation*, *25*(4), 293–305. doi: 10.1097/HTR.0b013e3181e67936
- MATLAB. (2016). *version 7.10.0 (r2016a)*. Natick, Massachusetts: The MathWorks Inc.
- MATLAB. (2016a). *Matlab computer vision system toolbox*. Natick, Massachusetts: The MathWorks Inc.
- MATLAB. (2019). *version 9.6.0 (r2019a)*. Natick, Massachusetts: The MathWorks Inc.

- Maylor, E. A., & Wing, A. M. (1996). Age differences in postural stability are increased by additional cognitive demands. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *51*(3), 143–154. doi: 10.1093/geronb/51B.3.P143
- McDonald, N. C. (2008). Children’s mode choice for the school trip: The role of distance and school location in walking to school. *Transportation*, *35*(1), 23–35. doi: 10.1007/s11116-007-9135-7
- McGraw, H. (2003). *Dictionary of scientific and technical terms*. Sybil P. Parker.
- McKnight, A. J., & McKnight, A. S. (1999). Multivariate analysis of age-related driver ability and performance deficits. *Accident Analysis & Prevention*, *31*(5), 445–454. doi: 10.1016/S0001-4575(98)00082-7
- Meir, A., Parmet, Y., & Oron-Gilad, T. (2013). Towards understanding child-pedestrians’ hazard perception abilities in a mixed reality dynamic environment. *Transportation Research Part F: Traffic Psychology and Behaviour*, *20*, 90–107. doi: 10.1016/j.trf.2013.05.004
- Miellet, S., Lao, J., & Caldara, R. (2014). An appropriate use of iMap produces correct statistical results: A reply to McManus (2013) “iMAP and iMAP2 produce erroneous statistical maps of eye-movement differences”. *Perception*, *43*(5), 451–457. doi: 10.1068/2Fp7682
- Mikl, M., Mareček, R., Hlušík, P., Pavlicová, M., Drastich, A., Chlebus, P., . . . Krupa, P. (2008). Effects of spatial smoothing on fMRI group inferences. *Magnetic Resonance Imaging*, *26*(4), 490–503. doi: 10.1016/j.mri.2007.08.006
- Milham, M. P., Erickson, K. I., Banich, M. T., Kramer, A. F., Webb, A., Wszalek, T., & Cohen, N. J. (2002). Attentional control in the aging brain: Insights from an fMRI study of the stroop task. *Brain and Cognition*, *49*(3), 277–296. doi: 10.1006/brcg.2001.1501
- Mishra, J., Zinni, M., Bavelier, D., & Hillyard, S. A. (2011). Neural basis of superior performance of action videogame players in an attention-demanding task. *Journal of Neuroscience*, *31*(3), 992–998. doi: 10.1523/JNEUROSCI.4834-10.2011

- Miskovic, V., & Keil, A. (2015). Reliability of event-related EEG functional connectivity during visual entrainment: Magnitude squared coherence and phase synchrony estimates. *Psychophysiology*, *52*(1), 81–89. doi: 10.1111/psyp.12287
- Mital, P. K., Smith, T. J., Hill, R. L., & Henderson, J. M. (2011). Clustering of gaze during dynamic scene viewing is predicted by motion. *Cognitive Computation*, *3*(1), 5–24. doi: 10.1007/s12559-010-9074-z
- Moran, E., Warden, D., Macleod, L., Mayes, G., & Gillies, J. (1997). Stranger-danger: What do children know? *Child Abuse Review: Journal of the British Association for the Study and Prevention of Child Abuse and Neglect*, *6*(1), 11–23.
- Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science*, *229*(4715), 782–784.
- Morcom, A. M., & Henson, R. N. A. (2018). Increased prefrontal activity with aging reflects nonspecific neural responses rather than compensation. *Journal of Neuroscience*, *38*(33), 7303–7313. doi: 10.1523/JNEUROSCI.1701-17.2018
- Morey, R. D., & Rouder, J. N. (2018). BayesFactor: Computation of Bayes Factors for Common Designs [Computer software manual]. Retrieved from <https://CRAN.R-project.org/package=BayesFactor> (R package version 0.9.12-4.2)
- Morgan, S., Hansen, J., & Hillyard, S. (1996). Selective attention to stimulus location modulates the steady-state visual evoked potential. *Proceedings of the National Academy of Sciences*, *93*(10), 4770–4774. doi: 10.1073/pnas.93.10.4770
- Morrongiello, B. A., Corbett, M., Milanovic, M., & Beer, J. (2015). Using a virtual environment to examine how children cross streets: Advancing our understanding of how injury risk arises. *Journal of Pediatric Psychology*, *41*(2), 265–275. doi: 10.1093/jpepsy/jsv078
- Moschner, C., & Baloh, R. W. (1994). Age-related changes in visual tracking. *Journal of Gerontology*, *49*(5), 235–238. doi: 10.1093/geronj/49.5.M235
- Müller, M. M., Teder-Sälejärvi, W., & Hillyard, S. A. (1998). The time course of cortical facilitation during cued shifts of spatial attention. *Nature Neuroscience*,

1(7), 631–634. doi: 10.1038/2865

- Munoz, D. P., Broughton, J. R., Goldring, J. E., & Armstrong, I. T. (1998). Age-related performance of human subjects on saccadic eye movement tasks. *Experimental Brain Research*, 121(4), 391–400.
- Munoz, D. P., & Everling, S. (2004). Look away: The anti-saccade task and the voluntary control of eye movement. *Nature Reviews. Neuroscience*, 5(3), 218–228. doi: 10.1038/nrn1345
- Nagamatsu, L. S., Voss, M., Neider, M. B., Gaspar, J. G., Handy, T. C., Kramer, A. F., & Liu-Ambrose, T. Y. (2011). Increased cognitive load leads to impaired mobility decisions in seniors at risk for falls. *Psychology and Aging*, 26(2), 253–259. doi: 10.1037/a0022929
- Nasr, S., Liu, N., Devaney, K. J., Yue, X., Rajimehr, R., Ungerleider, L. G., & Tootell, R. B. (2011). Scene-selective cortical regions in human and nonhuman primates. *Journal of Neuroscience*, 31(39), 13771–13785. doi: 10.1523/JNEUROSCI.2792-11.2011
- Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., ... Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: A brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society*, 53(4), 695–699. doi: 10.1111/j.1532-5415.2005.53221.x
- Neider, M. B., Gaspar, J. G., McCarley, J. S., Crowell, J. A., Kaczmariski, H., & Kramer, A. F. (2011). Walking and talking: Dual-task effects on street crossing behavior in older adults. *Psychology and Aging*, 26(2), 260–268. doi: 10.1037/a0021566
- NHTSA. (2007). Traffic safety facts. *Washington, DC: National Highway Traffic Safety Administration*.
- Nicholls, V. I., Jean-Charles, G., Lao, J., de Lissa, P., Caldara, R., & Miellet, S. (2019). Developing attentional control in naturalistic dynamic road crossing situations. *Scientific Reports*, 9(1), 4176. doi: 10.1038/s41598-019-39737-7
- Niemann, T., Lappe, M., Büscher, A., & Hoffmann, K.-P. (1999). Ocular responses

- to radial optic flow and single accelerated targets in humans. *Vision Research*, 39(7), 1359–1371. doi: 10.1016/S0042-6989(98)00236-3
- Nieuwenhuis, S., Ridderinkhof, K. R., De Jong, R., Kok, A., & Van Der Molen, M. W. (2000). Inhibitory inefficiency and failures of intention activation: Age-related decline in the control of saccadic eye movements. *Psychology and Aging*, 15(4), 635–647. doi: 10.1037/0882-7974.15.4.635
- Nobre, K., Nobre, A. C., & Kastner, S. (2014). *The Oxford handbook of attention*. Oxford University Press.
- Norcia, A. M., Appelbaum, L. G., Ales, J. M., Cottareau, B. R., & Ression, B. (2015). The steady-state visual evoked potential in vision research: A review. *Journal of Vision*, 15(6), 4–4. doi: 10.1167/15.6.4
- Olincy, A., Ross, R., Youngd, D., & Freedman, R. (1997). Age diminishes performance on an antisaccade eye movement task. *Neurobiology of Aging*, 18(5), 483–489. doi: 10.1016/S0197-4580(97)00109-7
- O’Neal, E. E., Jiang, Y., Franzen, L. J., Rahimian, P., Yon, J. P., Kearney, J. K., & Plumert, J. M. (2017). Changes in perception–action tuning over long time scales: How children and adults perceive and act on dynamic affordances when crossing roads. *Journal of Experimental Psychology: Human Perception and Performance*, 44(1), 18–26. doi: 10.1037/xhp0000378
- Owen, A. M., Downes, J. J., Sahakian, B. J., Polkey, C. E., & Robbins, T. W. (1990). Planning and spatial working memory following frontal lobe lesions in man. *Neuropsychologia*, 28(10), 1021–1034. doi: 10.1016/0028-3932(90)90137-D
- Owsley, C., Ball, K. K., Sloane, M. E., Roenker, D. L., & Bruni, J. R. (1991). Visual/cognitive correlates of vehicle accidents in older drivers. *Psychology and Aging*, 6(3), 403–415. doi: 10.1037/0882-7974.6.3.403
- Oxley, J. A., Fildes, B., Ihsen, E., Charlton, J., & Day, R. (1997). Differences in traffic judgements between young and old adult pedestrians. *Accident Analysis & Prevention*, 29(6), 839–847. doi: 10.1016/S0001-4575(97)00053-5
- Oxley, J. A., Ihsen, E., Fildes, B. N., Charlton, J. L., & Day, R. H. (2005). Crossing roads safely: An experimental study of age differences in gap se-

- lection by pedestrians. *Accident Analysis & Prevention*, *37*(5), 962–971. doi: 10.1016/j.aap.2005.04.017
- Paige, G. D. (1994). Senescence of human visual-vestibular interactions: Smooth pursuit, optokinetic, and vestibular control of eye movements with aging. *Experimental Brain Research*, *98*(2), 355–372. doi: 10.1007/BF00228423
- Painter, D. R., Dux, P. E., Travis, S. L., & Mattingley, J. B. (2014). Neural responses to target features outside a search array are enhanced during conjunction but not unique-feature search. *Journal of Neuroscience*, *34*(9), 3390–3401. doi: 10.1523/JNEUROSCI.3630-13.2014
- Palmer, E. M., Horowitz, T. S., Torralba, A., & Wolfe, J. M. (2011). What are the shapes of response time distributions in visual search? *Journal of Experimental Psychology: Human Perception and Performance*, *37*(1), 58–71. doi: 10.1037/a0020747
- Palmer, S. E. (1975). The effects of contextual scenes on the identification of objects. *Memory & Cognition*, *3*, 519–526. doi: 10.3758/BF03197524
- Palmer, S. E. (1992). Common region: A new principle of perceptual grouping. *Cognitive Psychology*, *24*(3), 436–447. doi: 10.1016/0010-0285(92)90014-S
- Paquette, C., & Fung, J. (2011). Old age affects gaze and postural coordination. *Gait & Posture*, *33*(2), 227–232. doi: 10.1016/j.gaitpost.2010.11.010
- Parasuraman, R., & Nestor, P. G. (1991). Attention and driving skills in aging and Alzheimer’s disease. *Human Factors*, *33*(5), 539–557. doi: 10.1177/2F001872089103300506
- Park, D. C., & Festini, S. B. (2017). Theories of memory and aging: A look at the past and a glimpse of the future. *The Journals of Gerontology: Series B*, *72*(1), 82–90. doi: 10.1093/geronb/gbw066
- Parkhurst, D., Law, K., & Niebur, E. (2002). Modeling the role of salience in the allocation of overt visual attention. *Vision research*, *42*(1), 107–123. doi: 10.1016/S0042-6989(01)00250-4
- Patla, A. E., & Vickers, J. N. (1997). Where and when do we look as we approach and step over an obstacle in the travel path? *NeuroReport*, *8*(17), 3661–3665.

- Paus, T. (1989). The development of sustained attention in children might be related to the maturation of frontal cortical functions. *Acta Neurobiologiae Experimentalis*, *49*(1), 51–55.
- Paus, T., Babenko, V., & Radil, T. (1990). Development of an ability to maintain verbally instructed central gaze fixation studied in 8-to 10-year-old children. *International Journal of Psychophysiology*, *10*(1), 53–61. doi: 10.1016/0167-8760(90)90045-F
- Peirce, J. W. (2007). Psychopy—psychophysics software in python. *Journal of Neuroscience Methods*, *162*(1-2), 8–13. doi: 10.1016/j.jneumeth.2006.11.017
- Pelz, J. B., & Canosa, R. (2001). Oculomotor behavior and perceptual strategies in complex tasks. *Vision Research*, *41*(25-26), 3587–3596. doi: 10.1016/S0042-6989(01)00245-0
- Percer, J. (2009). *Child pedestrian safety education: Applying learning and developmental theories to develop safe street-crossing behaviors* (Tech. Rep.). United States. National Highway Traffic Safety Administration.
- Pereira, E. J., & Castelhana, M. S. (2014). Peripheral guidance in scenes: The interaction of scene context and object content. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(5), 2056–2072. doi: 10.1037/a0037524
- Pernet, C. R., Chauveau, N., Gaspar, C., & Rousselet, G. A. (2011). LIMO EEG: A Toolbox for Hierarchical Linear Modeling of Electroencephalographic Data. *Computational Intelligence and Neuroscience*, *2011*, 1–11. doi: 10.1155/2011/831409
- Pernet, C. R., Latinus, M., Nichols, T. E., & Rousselet, G. A. (2015). Cluster-based computational methods for mass univariate analyses of event-related brain potentials/fields: A simulation study. *Journal of Neuroscience Methods*, *250*, 85–93. doi: 10.1016/j.jneumeth.2014.08.003
- Pernet, C. R., Wilcox, R. R., & Rousselet, G. A. (2013). Robust correlation analyses: False positive and power validation using a new open source Matlab toolbox. *Frontiers in Psychology*, *3*, 606. doi: 10.3389/fpsyg.2012.00606

- Phillips, L., Gilhooly, K., Logie, R., Sala, S. D., & Wynn, V. (2003). Age, working memory, and the Tower of London task. *European Journal of Cognitive Psychology, 15*(2), 291–312. doi: 10.1080/09541440244000148
- Pick, D. F., & Proctor, R. W. (1999). Age differences in the effects of irrelevant location information. *Automation technology and human performance, 258–261*.
- Pitcairn, T., & Edlmann, T. (2000). Individual differences in road crossing ability in young children and adults. *British Journal of Psychology, 91*(3), 391–410. doi: 10.1348/000712600161899
- Pitzalis, S., Sdoia, S., Bultrini, A., Committeri, G., Di Russo, F., Fattori, P., . . . Galati, G. (2013). Selectivity to translational egomotion in human brain motion areas. *PloS One, 8*(4), e60241. doi: 10.1371/journal.pone.0060241
- Plude, D. J., & Doussard-Roosevelt, J. A. (1989). Aging, selective attention, and feature integration. *Psychology and Aging, 4*(1), 98–115. doi: 10.1037/0882-7974.4.1.98
- Plude, D. J., Enns, J. T., & Brodeur, D. (1994). The development of selective attention: A life-span overview. *Acta Psychologica, 86*(2-3), 227–272. doi: 10.1016/0001-6918(94)90004-3
- Plumert, J. M., Kearney, J. K., & Cremer, J. F. (2004). Children’s perception of gap affordances: Bicycling across traffic-filled intersections in an immersive virtual environment. *Child Development, 75*(4), 1243–1253. doi: 10.1111/j.1467-8624.2004.00736.x
- Plumert, J. M., Kearney, J. K., & Cremer, J. F. (2007). Children’s road crossing: A window into perceptual–motor development. *Current Directions in Psychological Science, 16*(5), 255–258. doi: 10.1111/2Fj.1467-8721.2007.00515.x
- Ponds, R. W., Brouwer, W. H., & Van Wolffelaar, P. C. (1988). Age differences in divided attention in a simulated driving task. *Journal of Gerontology, 43*(6), 151–156. doi: 10.1093/geronj/43.6.P151
- Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*(1), 3–25. doi: 10.1080/2F00335558008248231

- Posner, M. I., Nissen, M. J., & Ogden, W. C. (1978). Attended and unattended processing modes: The role of set for spatial location. *Modes of Perceiving and Processing Information*, 2, 137-158.
- Posner, M. I., Snyder, C. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General*, 109(2), 160–174. doi: 10.1037/0096-3445.109.2.160
- Pryde, K. M., Roy, E. A., & Patla, A. E. (1997). Age-related trends in locomotor ability and obstacle avoidance. *Human Movement Science*, 16(4), 507–516. doi: 10.1016/S0167-9457(96)00064-4
- Punsawad, Y., & Wongsawat, Y. (2017). A multi-command SSVEP-based BCI system based on single flickering frequency half-field steady-state visual stimulation. *Medical & Biological Engineering & Computing*, 55(6), 965–977. doi: 10.1007/s11517-016-1560-3
- R Core Team. (2016). R: A language and environment for statistical computing [Computer software manual]. Vienna, Austria. Retrieved from <https://www.R-project.org>
- R Core Team. (2020). R: A language and environment for statistical computing [Computer software manual]. Vienna, Austria. Retrieved from <https://www.R-project.org/>
- Rajah, M. N., Languay, R., & Valiquette, L. (2010). Age-related changes in prefrontal cortex activity are associated with behavioural deficits in both temporal and spatial context memory retrieval in older adults. *Cortex*, 46(4), 535–549. doi: 10.1016/j.cortex.2009.07.006
- Rayner, K., Reichle, E. D., Stroud, M. J., Williams, C. C., & Pollatsek, A. (2006). The effect of word frequency, word predictability, and font difficulty on the eye movements of young and older readers. *Psychology and Aging*, 21(3), 448–465.
- Raz, N., Gunning, F. M., Head, D., Dupuis, J. H., McQuain, J., Briggs, S. D., ... Acker, J. (1997). Selective aging of the human cerebral cortex observed in vivo: Differential vulnerability of the prefrontal gray matter. *Cerebral Cortex*,

7(3), 268–282. doi: 10.1093/cercor/7.3.268

- Raz, N., Lindenberger, U., Rodrigue, K. M., Kennedy, K. M., Head, D., Williamson, A., . . . Acker, J. D. (2005). Regional brain changes in aging healthy adults: General trends, individual differences and modifiers. *Cerebral Cortex*, *15*(11), 1676–1689. doi: 10.1093/cercor/bhi044
- Renton, A. I., Painter, D. R., & Mattingley, J. B. (2019). Differential deployment of visual attention during interactive approach and avoidance behavior. *Cerebral Cortex*, *29*(6), 2366–2383. doi: 10.1093/cercor/bhy105
- Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive aging and the compensation hypothesis. *Current Directions in Psychological Science*, *17*(3), 177–182. doi: 10.1111/2Fj.1467-8721.2008.00570.x
- Reynolds, J. H., Chelazzi, L., & Desimone, R. (1999). Competitive mechanisms subserve attention in macaque areas V2 and V4. *Journal of Neuroscience*, *19*(5), 1736–1753.
- Risko, E. F., Laidlaw, K. E., Freeth, M., Foulsham, T., & Kingstone, A. (2012). Social attention with real versus reel stimuli: Toward an empirical approach to concerns about ecological validity. *Frontiers in Human Neuroscience*, *6*, 143. doi: 10.3389/fnhum.2012.00143
- Ritchie, S. J., Tucker-Drob, E. M., & Deary, I. J. (2014). A strong link between speed of visual discrimination and cognitive ageing. *Current Biology*, *24*(15), 681–683. doi: 10.1016/j.cub.2014.06.012
- Rizzolatti, G., Riggio, L., Dascola, I., & Umiltá, C. (1987). Reorienting attention across the horizontal and vertical meridians: Evidence in favor of a premotor theory of attention. *Neuropsychologia*, *25*(1), 31–40. doi: 10.1016/0028-3932(87)90041-8
- Rogers, R. D., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of experimental psychology: General*, *124*(2), 207–231. doi: 10.1037/0096-3445.124.2.207
- Roggeveen, A. B., Prime, D. J., & Ward, L. M. (2007). Lateralized readiness potentials reveal motor slowing in the aging brain. *The Journals of Gerontology*

- Series B: Psychological Sciences and Social Sciences*, 62(2), P78–P84. doi: 10.1093/geronb/62.2.P78
- Romoser, M. R., Pollatsek, A., Fisher, D. L., & Williams, C. C. (2013). Comparing the glance patterns of older versus younger experienced drivers: Scanning for hazards while approaching and entering the intersection. *Transportation Research Part F: Traffic Psychology and Behaviour*, 16, 104–116. doi: 10.1016/j.trf.2012.08.004
- Ross, R. G., Olincy, A., Harris, J. G., Radant, A., Adler, L. E., Compagnon, N., & Freedman, R. (1999). The effects of age on a smooth pursuit tracking task in adults with schizophrenia and normal subjects. *Biological Psychiatry*, 46(3), 383–391. doi: 10.1016/S0006-3223(98)00369-2
- Ross, R. G., Radant, A. D., Hommer, D. W., & Young, D. A. (1994). Saccadic eye movements in normal children from 8 to 15 years of age: A developmental study of visuospatial attention. *Journal of Autism and Developmental Disorders*, 24(4), 413–431. doi: 10.1007/BF02172126
- Rothkopf, C. A., Ballard, D. H., & Hayhoe, M. M. (2007). Task and context determine where you look. *Journal of Vision*, 7(14), 16–16. doi: 10.1167/7.14.16
- Rousselet, G. A., Pernet, C., & Wilcox, R. R. (2019). A practical introduction to the bootstrap: A versatile method to make inferences by using data-driven simulations.  
doi: 10.31234/osf.io/h8ft7
- Rousselet, G. A., Pernet, C. R., & Wilcox, R. R. (2017). Beyond differences in means: Robust graphical methods to compare two groups in neuroscience. *European Journal of Neuroscience*, 46(2), 1738–1748. doi: 10.1111/ejn.13610
- RStudio Team. (2016). RStudio: Integrated Development Environment for R [Computer software manual]. Boston, MA. Retrieved from <http://www.rstudio.com/>
- Rypma, B., & D’Esposito, M. (2000). Isolating the neural mechanisms of age-related changes in human working memory. *Nature Neuroscience*, 3(5), 509–515. doi: 10.1038/74889

- Salat, D. H., Buckner, R. L., Snyder, A. Z., Greve, D. N., Desikan, R. S., Busa, E., . . . Fischl, B. (2004). Thinning of the cerebral cortex in aging. *Cerebral Cortex*, *14*(7), 721–730. doi: 10.1093/cercor/bhh032
- Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, *103*(3), 403–428.
- Sanders, A. F. (1970). Some aspects of the selective process in the functional visual field. *Ergonomics*, *13*(1), 101–117. doi: 10.1080/00140137008931124
- Sangani, S., Fung, J., Kizony, R., Koenig, S. T., & Weiss, P. L. (2013). Navigating and shopping in a complex virtual urban mall to evaluate cognitive functions. *International Conference on Virtual Rehabilitation (ICVR)*, 9–14. doi: 10.1109/ICVR.2013.6662098
- Schärli, A. M., van de Langenberg, R., Murer, K., & Müller, R. (2012). The influence of gaze behaviour on postural control from early childhood into adulthood. *Gait & Posture*, *36*(1), 78–84. doi: 10.1016/j.gaitpost.2012.01.008
- Schärli, A. M., van de Langenberg, R., Murer, K., & Müller, R. (2013). Postural control and head stability during natural gaze behaviour in 6-to 12-year-old children. *Experimental Brain Research*, *227*(4), 523–534. doi: 10.1007/s00221-013-3528-y
- Schneider, B. A., & Pichora-Fuller, M. K. (2000). Implications of perceptual deterioration for cognitive aging research. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (p. 155–219). Lawrence Erlbaum Associates Publishers.
- Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological Review*, *84*(1), 1–66.
- Schneider-Garces, N. J., Gordon, B. A., Brumback-Peltz, C. R., Shin, E., Lee, Y., Sutton, B. P., . . . Fabiani, M. (2010). Span, CRUNCH, and beyond: Working memory capacity and the aging brain. *Journal of Cognitive Neuroscience*, *22*(4), 655–669. doi: 10.1162/jocn.2009.21230
- Schul, R., Townsend, J., & Stiles, J. (2003). The development of attentional orient-

- ing during the school-age years. *Developmental Science*, 6(3), 262–272. doi: 10.1111/1467-7687.00282
- Schwebel, D. C., Combs, T., Rodriguez, D., Severson, J., & Sisiopiku, V. (2016). Community-based pedestrian safety training in virtual reality: A pragmatic trial. *Accident Analysis & Prevention*, 86, 9–15. doi: 10.1016/j.aap.2015.10.002
- Schwebel, D. C., Davis, A. L., & O’Neal, E. E. (2012). Child pedestrian injury: A review of behavioral risks and preventive strategies. *American Journal of Lifestyle Medicine*, 6(4), 292–302. doi: 10.1177/2F0885066611404876
- Schwebel, D. C., Gaines, J., & Severson, J. (2008). Validation of virtual reality as a tool to understand and prevent child pedestrian injury. *Accident Analysis & Prevention*, 40(4), 1394–1400. doi: 10.1016/j.aap.2008.03.005
- Scialfa, C. T., & Joffe, K. M. (1997). Age differences in feature and conjunction search: Implications for theories of visual search and generalized slowing. *Aging, Neuropsychology, and Cognition*, 4(3), 227–246. doi: 10.1080/13825589708256649
- Scialfa, C. T., Kline, D. W., & Lyman, B. J. (1987). Age differences in target identification as a function of retinal location and noise level: Examination of the useful field of view. *Psychology and Aging*, 2(1), 14–19. doi: 10.1037/0882-7974.2.1.14
- Scialfa, C. T., Thomas, D. M., Joffe, K. M., et al. (1994). Age differences in the useful field of view: An eye movement analysis. *Optometry and Vision Science*, 71(12), 736–742. doi: 10.1097/00006324-199412000-00003
- Sekuler, R., & Ball, K. K. (1986). Visual localization: Age and practice. *Journal of the Optical Society of America A*, 3(6), 864–867. doi: 10.1364/JOSAA.3.000864
- Sekuler, R., McLaughlin, C., & Yotsumoto, Y. (2008). Age-related changes in attentional tracking of multiple moving objects. *Perception*, 37(6), 867–876.
- Seya, Y., & Mori, S. (2012). Spatial attention and reaction times during smooth pursuit eye movement. *Attention, Perception, & Psychophysics*, 74(3), 493–

509. doi: 10.3758/s13414-011-0247-y

- Shallice, T. (1982). Specific impairments of planning. *Philosophical Transactions of the Royal Society of London. B, Biological Sciences*, 298(1089), 199–209. doi: 10.1098/rstb.1982.0082
- Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending and a general theory. *Psychological Review*, 84(2), 127–190. doi: 10.1037/0033-295X.84.2.127
- Shinar, D., Zaidel, D. M., & Paarlberg, W. T. (1978). *Driver performance and individual differences in attention and information processing* (Vol. 1). US Department of Transportation.
- Simpson, G., Johnston, L., & Richardson, M. (2003). An investigation of road crossing in a virtual environment. *Accident Analysis & Prevention*, 35(5), 787–796. doi: 10.1016/S0001-4575(02)00081-7
- Sivak, M., Olson, P. L., & Pastalan, L. A. (1981). Effect of driver's age on nighttime legibility of highway signs. *Human Factors*, 23(1), 59–64. doi: 10.1177/2F001872088102300106
- Slessor, G., Laird, G., Phillips, L. H., Bull, R., & Filippou, D. (2010). Age-related differences in gaze following: Does the age of the face matter? *Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, 65(5), 536–541. doi: 10.1093/geronb/gbq038
- Slessor, G., Phillips, L. H., & Bull, R. (2008). Age-related declines in basic social perception: Evidence from tasks assessing eye-gaze processing. *Psychology and Aging*, 23(4), 812–822. doi: 10.1037/a0014348
- Smilek, D., Birmingham, E., Cameron, D., Bischof, W., & Kingstone, A. (2006). Cognitive ethology and exploring attention in real-world scenes. *Brain Research*, 1080(1), 101–119. doi: 10.1016/j.brainres.2005.12.090
- Smith, D. T., & Schenk, T. (2012). The premotor theory of attention: Time to move on? *Neuropsychologia*, 50(6), 1104–1114. doi: 10.1016/j.neuropsychologia.2012.01.025

- Smith, T. J. (2013). Watching you watch movies: Using eye tracking to inform film theory. In A. Shimamura (Ed.), *Psychocinematics: Exploring cognition at the movies*. (pp. 165–191). Oxford University Press.
- Smith, T. J., & Mital, P. K. (2013). Attentional synchrony and the influence of viewing task on gaze behavior in static and dynamic scenes. *Journal of Vision*, *13*(8), 16–16. doi: 10.1167/13.8.16
- Sparrow, W., Bradshaw, E. J., Lamoureux, E., & Tirosh, O. (2002). Ageing effects on the attention demands of walking. *Human Movement Science*, *21*(5-6), 961–972. doi: 10.1016/S0167-9457(02)00154-9
- Spreng, R. N., Mar, R. A., & Kim, A. S. N. (2009). The common neural basis of autobiographical memory, prospection, navigation, theory of mind, and the default mode: A quantitative meta-analysis. *Journal of Cognitive Neuroscience*, *21*(3), 489–510. doi: 10.1162/jocn.2008.21029
- Stanley, J., & Hollands, M. (2014). A novel video-based paradigm to study the mechanisms underlying age-and falls risk-related differences in gaze behaviour during walking. *Ophthalmic and Physiological Optics*, *34*(4), 459–469. doi: 10.1111/opo.12137
- Stine, E. A., & Wingfield, A. (1990). How much do working memory deficits contribute to age differences in discourse memory? *European Journal of Cognitive Psychology*, *2*(3), 289–304. doi: 10.1080/09541449008406209
- Störmer, V. S., Winther, G. N., Li, S.-C., & Andersen, S. K. (2013). Sustained multifocal attentional enhancement of stimulus processing in early visual areas predicts tracking performance. *Journal of Neuroscience*, *33*(12), 5346–5351. doi: 10.1523/JNEUROSCI.4015-12.2013
- Stubbs, J. L., Corrow, S. L., Kiang, B., Panenka, W. J., & Barton, J. J. S. (2018). The effects of enhanced attention and working memory on smooth pursuit eye movement. *Experimental Brain Research*, *236*(2), 485–495. doi: 10.1007/s00221-017-5146-6
- Sundberg, K. A., Mitchell, J. F., & Reynolds, J. H. (2009). Spatial attention modulates center-surround interactions in macaque visual area V4. *Neuron*,

61(6), 952–963. doi: 10.1016/j.neuron.2009.02.023

- Tabibi, Z., & Pfeffer, K. (2003). Choosing a safe place to cross the road: The relationship between attention and identification of safe and dangerous road-crossing sites. *Child: Care, Health and Development*, 29(4), 237–244. doi: 10.1046/j.1365-2214.2003.00336.x
- Tapiro, H., Borowsky, A., Oron-Gilad, T., & Parmet, Y. (2016). Where do older pedestrians glance before deciding to cross a simulated two-lane road? A pedestrian simulator paradigm. In *Proceedings of the human factors and ergonomics society annual meeting* (Vol. 60, pp. 11–15). doi: 10.1177/2F1541931213601003
- Tapiro, H., Meir, A., Parmet, Y., & Oron-Gilad, T. (2014). Visual search strategies of child-pedestrians in road crossing tasks. In D. de Waard et al. (Eds.), *Proceedings of the human factors and ergonomics society*. Perception.
- Tatler, B. W., Hayhoe, M. M., Land, M. F., & Ballard, D. H. (2011). Eye guidance in natural vision: Reinterpreting salience. *Journal of Vision*, 11(5), 5–5. doi: 10.1167/11.5.5
- Tatler, B. W., & Vincent, B. T. (2009). The prominence of behavioural biases in eye guidance. *Visual Cognition*, 17(6-7), 1029–1054. doi: 10.1080/13506280902764539
- te Velde, A. F., van der Kamp, J., Barela, J. A., & Savelsbergh, G. J. (2005). Visual timing and adaptive behavior in a road-crossing simulation study. *Accident Analysis & Prevention*, 37(3), 399–406. doi: 10.1016/j.aap.2004.12.002
- 't Hart, B. M., Vockeroth, J., Schumann, F., Bartl, K., Schneider, E., Koenig, P., & Einhäuser, W. (2009). Gaze allocation in natural stimuli: Comparing free exploration to head-fixed viewing conditions. *Visual Cognition*, 17(6-7), 1132–1158. doi: 10.1080/13506280902812304
- Theeuwes, J., Atchley, P., & Kramer, A. F. (2000). On the time course of top-down and bottom-up control of visual attention. In S. Monsell & J. Driver (Eds.), *Control of cognitive processes: Attention and performance xviii* (pp. 105–124). Cambridge, MA: MIT Press.

- Thomas, N. M., Donovan, T., Dewhurst, S., & Bampouras, T. M. (2018). Visually fixating or tracking another person decreases balance control in young and older females walking in a real-world scenario. *Neuroscience Letters*, *677*, 78–83. doi: 10.1016/j.neulet.2018.04.038
- Thomson, J. A., Ampofo-Boateng, K., Pitcairn, T., Grieve, R., Lee, D. N., & Demetre, J. D. (1992). Behavioural group training of children to find safe routes to cross the road. *British Journal of Educational Psychology*, *62*(2), 173–183. doi: 10.1111/j.2044-8279.1992.tb01011.x
- Thomson, J. A., Tolmie, A., Foot, H. C., & McLaren, B. (1996). *Child development and the aims of road safety education* (Tech. Rep.).
- Thomson, J. A., Tolmie, A. K., Foot, H. C., Whelan, K. M., Sarvary, P., & Morrison, S. (2005). Influence of virtual reality training on the roadside crossing judgments of child pedestrians. *Journal of Experimental Psychology: Applied*, *11*(3), 175–186. doi: 10.1037/1076-898X.11.3.175
- Thomson, J. A., & Whelan, K. M. (1997). *A community approach to road safety education using practical training methods: The Drumchapel project* (Tech. Rep.).
- Tibshirani, R. (1996). Regression shrinkage and selection via the lasso. *Journal of the Royal Statistical Society: Series B (Methodological)*, *58*(1), 267–288. doi: 10.1111/j.2517-6161.1996.tb02080.x
- Timperio, A., Crawford, D., Telford, A., & Salmon, J. (2004). Perceptions about the local neighborhood and walking and cycling among children. *Preventive Medicine*, *38*(1), 39–47. doi: 10.1016/j.ypmed.2003.09.026
- Tipper, S. P. (1991). Less attentional selectivity as a result of declining inhibition in older adults. *Bulletin of the Psychonomic Society*, *29*(1), 45–47. doi: 10.3758/BF03334765
- Toffanin, P., de Jong, R., Johnson, A., & Martens, S. (2009). Using frequency tagging to quantify attentional deployment in a visual divided attention task. *International Journal of Psychophysiology*, *72*(3), 289–298. doi: 10.1016/j.ijpsycho.2009.01.006

- Tomlie, A., McLaren, B., Foot, H., Thomson, J. A., & Whelan, K. (1998). Problems of attention and visual search in the context of child pedestrian behaviour. *Road Safety Research Report no. 8.*
- Torralba, A., Oliva, A., Castelhana, M. S., & Henderson, J. M. (2006). Contextual guidance of eye movements and attention in real-world scenes: The role of global features in object search. *Psychological Review*, *113*(4), 766–786. doi: 10.1037/0033-295X.113.4.766
- Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136. doi: 10.1016/0010-0285(80)90005-5
- Treitz, F. H., Heyder, K., & Daum, I. (2007). Differential course of executive control changes during normal aging. *Aging, Neuropsychology, and Cognition*, *14*(4), 370–393. doi: 10.1080/13825580600678442
- Trick, L. M., Jaspers-Fayer, F., & Sethi, N. (2005). Multiple-object tracking in children: The “catch the spies” task. *Cognitive Development*, *20*(3), 373–387. doi: 10.1016/j.cogdev.2005.05.009
- Tsang, P. S. (1998). Age, attention, expertise, and time-sharing performance. *Psychology and Aging*, *13*(2), 323–347. doi: 10.1037/0882-7974.13.2.323
- Underwood, G., Foulsham, T., van Loon, E., Humphreys, L., & Bloyce, J. (2006). Eye movements during scene inspection: A test of the saliency map hypothesis. *European Journal of Cognitive Psychology*, *18*(3), 321–342. doi: 10.1080/09541440500236661
- Van der Linden, M., Brédart, S., & Beerten, A. (1994). Age-related differences in updating working memory. *British Journal of Psychology*, *85*(1), 145–152. doi: 10.1111/j.2044-8295.1994.tb02514.x
- Van der Lubbe, R. H., & Verleger, R. (2002). Aging and the Simon task. *Psychophysiology*, *39*(1), 100–110. doi: 10.1111/1469-8986.3910100
- Van Der Molen, H. H. (1981). Child pedestrian’s exposure, accidents and behavior. *Accident Analysis & Prevention*, *13*(3), 193–224. doi: 10.1016/0001-4575(81)90005-1
- Van Donkelaar, P., & Drew, A. S. (2002). The allocation of attention during smooth

- pursuit eye movements. In *Progress in brain research* (Vol. 140, pp. 267–277). Elsevier. doi: 10.1016/S0079-6123(02)40056-8
- Vanegas, M. I., Blangero, A., & Kelly, S. P. (2015). Electrophysiological indices of surround suppression in humans. *Journal of Neurophysiology*, *113*(4), 1100–1109. doi: 10.1152/jn.00774.2014
- Van Helden, P. (2013). Data-driven hypotheses. *EMBO Reports*, *14*(2), 104. doi: 10.1038/embor.2012.207
- Vann, S. D., Aggleton, J. P., & Maguire, E. A. (2009). What does the retrosplenial cortex do? *Nature Reviews Neuroscience*, *10*(11), 792–802. doi: 10.1038/nrn2733
- Vansteenkiste, P., Zeuwts, L., van Maarseveen, M., Cardon, G., Savelsbergh, G., & Lenoir, M. (2017). The implications of low quality bicycle paths on the gaze behaviour of young learner cyclists. *Transportation Research Part F: Traffic Psychology and Behaviour*, *48*, 52–60. doi: 10.1016/j.trf.2017.04.013
- Veiel, L. L., Storandt, M., & Abrams, R. A. (2006). Visual search for change in older adults. *Psychology and Aging*, *21*(4), 754–762. doi: 10.1037/0882-7974.21.4.754
- Verhaeghen, P., Martin, M., & Sedek, G. (2012). Reconnecting cognition in the lab and cognition in real life: The role of compensatory social and motivational factors in explaining how cognition ages in the wild. *Aging, Neuropsychology, and Cognition*, *19*(1-2), 1–12. doi: 10.1080/13825585.2011.645009
- Vidal, M., Bulling, A., & Gellersen, H. (2012). Detection of smooth pursuits using eye movement shape features. In *Proceedings of the symposium on eye tracking research and applications* (pp. 177–180). doi: 10.1145/2168556.2168586
- Võ, M. L.-H., & Henderson, J. M. (2010). The time course of initial scene processing for eye movement guidance in natural scene search. *Journal of Vision*, *10*(3), 14–14. doi: 10.1167/10.3.14
- Võ, M. L.-H., & Wolfe, J. M. (2012). When does repeated search in scenes involve memory? Looking at versus looking for objects in scenes. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(1), 23–41. doi:

- Voit, E. O. (2019). Perspective: Dimensions of the scientific method. *PLoS Computational Biology*, *15*(9), e1007279. doi: 10.1371/journal.pcbi.1007279
- Vu, K.-P. L., & Proctor, R. W. (2008). Age differences in response selection for pure and mixed stimulus–response mappings and tasks. *Acta Psychologica*, *129*(1), 49–60. doi: 10.1016/j.actpsy.2008.04.006
- Wagenmakers, E. J., Love, J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., . . . Morey, R. D. (2018). Bayesian inference for psychology. Part II: Example applications with JASP. *Psychonomic Bulletin & Review*, *25*(1), 58–76. doi: 10.3758/s13423-017-1323-7
- Wall, M. B., & Smith, A. T. (2008). The representation of egomotion in the human brain. *Current Biology*, *18*(3), 191–194. doi: 10.1016/j.cub.2007.12.053
- Waszak, F., Li, S.-C., & Hommel, B. (2010). The development of attentional networks: Cross-sectional findings from a life span sample. *Developmental Psychology*, *46*(2), 337–349. doi: 10.1037/a0018541
- Weale, R. A. (1961). Retinal illumination and age. *Transactions of the Illuminating Engineering Society*, *26*, 95–100. doi: 10.1177/2F147715356102600204
- Welsh, M., Cicerello, A., Cuneo, K., & Brennan, M. (1995). Error and temporal patterns in Tower of Hanoi performance: Cognitive mechanisms and individual differences. *The Journal of General Psychology*, *122*(1), 69–81. doi: 10.1080/00221309.1995.9921223
- Wendelken, C., O’Hare, E. D., Whitaker, K. J., Ferrer, E., & Bunge, S. A. (2011). Increased functional selectivity over development in rostralateral prefrontal cortex. *Journal of Neuroscience*, *31*(47), 17260–17268. doi: 10.1523/JNEUROSCI.1193-10.2011
- Wertheimer, M. (1923). Untersuchungen zur Lehre von der Gestalt. II. *Psychologische Forschung*, *4*(1), 301–350. doi: 10.1007/BF00410640
- West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin*, *120*(2), 272–292.
- West, R. L. (2000). In defense of the frontal lobe hypothesis of cognitive aging.

- Journal of the International Neuropsychological Society*, 6(6), 727–729. doi: 10.1017/S1355617700666109
- White, A. L., Rolfs, M., & Carrasco, M. (2013). Adaptive deployment of spatial and feature-based attention before saccades. *Vision Research*, 85, 26–35. doi: 10.1016/j.visres.2012.10.017
- Whitebread, D., & Neilson, K. (2000). The contribution of visual search strategies to the development of pedestrian skills by 4-11 year-old children. *British Journal of Educational Psychology*, 70(4), 539–557. doi: 10.1348/000709900158290
- Whiting, W. L., Madden, D. J., Pierce, T. W., & Allen, P. A. (2005). Searching from the top down: Ageing and attentional guidance during singleton detection. *The Quarterly Journal of Experimental Psychology Section A*, 58(1), 72–97. doi: 10.1080/2F02724980443000205
- Wilcox, R. R., & Rousselet, G. A. (2018). A guide to robust statistical methods in neuroscience. *Current Protocols in Neuroscience*, 82(1), 8–42. doi: 10.1002/cpns.41
- Williams, E. H., Cristino, F., & Cross, E. S. (2019). Human body motion captures visual attention and elicits pupillary dilation. *Cognition*, 193, 104029. doi: 10.1016/j.cognition.2019.104029
- Wilson, B. A., Alderman, N., Burgess, P. W., Emslie, H., & Evans, J. (1996). *Behavioural assessment of the dysexecutive syndrome*. Thames Valley Test Company.
- Wilson, M. R., Miles, C. A., Vine, S. J., & Vickers, J. N. (2013). Quiet eye distinguishes children of high and low motor coordination abilities. *Medicine & Science in Sports & Exercise*, 45(6), 1144–1151.
- Wolfe, J. M. (1998). What can 1 million trials tell us about visual search? *Psychological Science*, 9(1), 33–39. doi: 10.1111/2F1467-9280.00006
- Wolfe, J. M., Võ, M. L.-H., Evans, K. K., & Greene, M. R. (2011). Visual search in scenes involves selective and nonselective pathways. *Trends in Cognitive Sciences*, 15(2), 77–84. doi: 10.1016/j.tics.2010.12.001
- World Health Organization. (2013). *Pedestrian safety: a road safety manual for*

- decision-makers and practitioners*. World Health Organization.
- World Health Organization. (2015). *Ten strategies for keeping children safe on the road*. World Health Organization.
- Wu, H.-Y., Rubinstein, M., Shih, E., Guttag, J., Durand, F., & Freeman, W. T. (2012). Eulerian video magnification for revealing subtle changes in the world. *ACM Transactions on Graphics*, *31*(4), 65:1–65:8. doi: 10.1145/2185520.2185561
- Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *10*(5), 601–621. doi: 10.1037/0096-1523.10.5.601
- Ybarra, O., Burnstein, E., Winkielman, P., Keller, M. C., Manis, M., Chan, E., & Rodriguez, J. (2008). Mental exercising through simple socializing: Social interaction promotes general cognitive functioning. *Personality and Social Psychology Bulletin*, *34*(2), 248–259. doi: 10.1177/2F0146167207310454
- Zeedyk, M. S., & Kelly, L. (2003). Behavioural observations of adult–child pairs at pedestrian crossings. *Accid. Anal. & Prev.*, *35*(5), 771–776. doi: 10.1016/S0001-4575(02)00086-6
- Zeedyk, M. S., Wallace, L., & Spry, L. (2002). Stop, look, listen, and think?: What young children really do when crossing the road. *Accident Analysis & Prevention*, *34*(1), 43–50. doi: 10.1016/S0001-4575(00)00101-9
- Zettel, J. L., Scovil, C. Y., McIlroy, W. E., & Maki, B. E. (2007). Gaze behaviour governing balance recovery in an unfamiliar and complex environment. *Neuroscience Letters*, *422*(3), 207–212. doi: 10.1016/j.neulet.2007.06.020
- Zeuwts, L. H., Vansteenkiste, P., Deconinck, F. J., Cardon, G., & Lenoir, M. (2017). Hazard perception in young cyclists and adult cyclists. *Accident Analysis & Prevention*, *105*, 64–71. doi: 10.1016/j.aap.2016.04.034
- Zhou, Y., Liang, L., Pan, Y., Qian, N., & Zhang, M. (2017). Sites of overt and covert attention define simultaneous spatial reference centers for visuomotor response. *Scientific Reports*, *7*, 46556. doi: 10.1038/srep46556
- Zietz, D., & Hollands, M. (2009). Gaze behavior of young and older adults

during stair walking. *Journal of Motor Behavior*, 41(4), 357–366. doi: 10.3200/JMBR.41.4.357-366

Zito, G. A., Cazzoli, D., Scheffler, L., Jäger, M., Müri, R. M., Mosimann, U. P., ... Nef, T. (2015). Street crossing behavior in younger and older pedestrians: An eye-and head-tracking study. *BMC geriatrics*, 15(1), 176. doi: 10.1186/s12877-015-0175-0

't Hart, B. M., & Einhäuser, W. (2012). Mind the step: Complementary effects of an implicit task on eye and head movements in real-life gaze allocation. *Experimental Brain Research*, 223(2), 233–249. doi: 10.1007/s00221-012-3254-

x