

AUGMENTING VISUAL PERCEPTION WITH GAZE-CONTINGENT DISPLAYS

Michael Mauderer

**A Thesis Submitted for the Degree of PhD
at the
University of St Andrews**



2017

**Full metadata for this item is available in
St Andrews Research Repository
at:**

<http://research-repository.st-andrews.ac.uk/>

Please use this identifier to cite or link to this item:

<http://hdl.handle.net/10023/11049>

This item is protected by original copyright

**This item is licensed under a
Creative Commons Licence**

Augmenting Visual Perception with Gaze-contingent Displays

Michael Mauderer



University of
St Andrews

This thesis is submitted in partial fulfilment for the degree of
Doctor of Philosophy
at the University of St Andrews

November 2016

ABSTRACT

Cheap and easy to use eye tracking can be used to turn a common display into a gaze-contingent display: a system that can react to the user's gaze and adjust its content based on where an observer is looking. This can be used to enhance the rendering on screens based on perceptual insights and the knowledge about what is currently seen. This thesis investigates how GCDs can be used to support aspects of depth and colour perception.

This thesis presents experiments that investigate the effects of simulated depth of field and chromatic aberration on depth perception. It also investigates how changing the colours surrounding the attended area can be used to influence the perceived colour and how this can be used to increase colour differentiation of colour and potentially increase the perceived gamut of the display.

The presented investigations and empirical results lay the foundation for future investigations and development of gaze-contingent technologies, as well as for general applications of colour and depth perception.

The results show that GCDs can be used to support the user in tasks that are related to visual perception. The presented techniques could be used to facilitate common tasks like distinguishing the depth of objects in virtual environments or discriminating similar colours in information visualisations.

ACKNOWLEDGEMENTS

First, I want to express my deepest thanks to my supervisor, Miguel Nacenta, who took me on as his first PhD student. Miguel provided me with fantastic guidance and constant support as well as the regular dose of Fish and Chips, which it turns out all is required to succeed in research.

I also want to thank my co-supervisor, Alex Voss, my reviewer, Chris Jefferson as well as my exam committee consisting of Aaron Quigley and Hans Gellersen, whom all have given me valuable feedback on my work.

The work in this thesis would not have been possible without my great collaborators, whom I have had the pleasure to work with over the years: Simone Conte, Dhanraj Vishwanath, Thomas Mansencal and David Flatla.

I thank all colleagues and friends in and around SACHI who have provided a friendly and supportive environment and, most importantly, lots and lots of fantastic cakes. I also want to especially mention Anne-Marie Mann, who joined me in our small thesis writing club and Jason T. Jacques with whom I had many enlightening discussions about British culture.

Many thanks also go to my friends and colleagues from Saarbrücken, who got me started on the path to HCI research and made sure that I would not get bored by a lack of side projects. Thanks, Pascal Lessel, Frederic Kerber, Florian Daiber and Antonio Krüger.

On a personal note, I also want to thank my parents Christine and Wilhelm Mauderer, and my sister, Bianca Mauderer, for their support and help over the years. And a huge thanks also goes to Uta Hinrichs, who has helped me, especially in the last stages of my PhD, by inspiring me, lifting my spirits and giving me a place to stay as well as a home.

DECLARATION

Candidate's Declarations

I, Michael Mauderer, hereby certify that this thesis, which is approximately 28000 words in length, has been written by me, that it is the record of work carried out by me and that it has not been submitted in any previous application for a higher degree.

I was admitted as a research student and as a candidate for the degree of Doctor of Philosophy in October, 2012; the higher study for which this is a record was carried out in the University of St Andrews between 2012 and 2016.

Date:

Signature of candidate:

Supervisor's Declaration

I hereby certify that the candidate has fulfilled the conditions of the Resolution and Regulations appropriate for the degree of Doctor of Philosophy in the University of St Andrews and that the candidate is qualified to submit this thesis in application for that degree.

Date:

Signature of supervisor:

PERMISSION FOR ELECTRONIC PUBLICATION

In submitting this thesis to the University of St Andrews I understand that I am giving permission for it to be made available for use in accordance with the regulations of the University Library for the time being in force, subject to any copyright vested in the work not being affected thereby. I also understand that the title and the abstract will be published, and that a copy of the work may be made and supplied to any bona fide library or research worker, that my thesis will be electronically accessible for personal or research use unless exempt by award of an embargo as requested below, and that the library has the right to migrate my thesis into new electronic forms as required to ensure continued access to the thesis. I have obtained any third-party copyright permissions that may be required in order to allow such access and migration, or have requested the appropriate embargo below.

The following is an agreed request by candidate and supervisor regarding the electronic publication of this thesis:

Access to printed copy and electronic publication of thesis through the University of St Andrews.

Date:

Signature of candidate:

Signature of supervisor:

DATA MANAGEMENT

Where data has been collected during any evaluation, case study or experiment, the data is being managed according to the permission agreed to by the participants through the consent forms. This generally means that the collected data is only available to the researchers directly involved in the evaluation due to the potentially private and sensitive nature of the collected data (most commonly images of people's likeness). The results of and findings from the evaluations are presented in the relevant parts of the thesis.

In accordance with the participants' consent, all data collected from the participants is stored securely within a locked office and will be deleted or safely disposed of within three (3) years of collection. This includes collected images, questionnaire and answer sheets or any other data provided by the participants.

PUBLICATIONS

Some ideas and figures described in this thesis have been published previously. The following list gives an overview of these publications. Each reference is followed by a short description outlining each authors work on the project as well as the thesis part where it is used.

CONFERENCE PAPERS (PEER REVIEWED)

- **Michael Mauderer**, Simone Conte, Miguel A. Nacenta and Dhanraj Vishwanath. Depth Perception with Gaze-contingent Depth of Field (2014) In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems CHI'14 (10 pages, Honorable Mention Award).

The second part of this paper builds the basis for Chapter 4. The experiment described in this thesis was designed, carried out and analysed by me, with feedback from Miguel Nacenta and Dhanraj Vishwanath. The text that builds the foundation for this chapter was written and edited in collaboration with Miguel Nacenta and with feedback from Dhanraj Vishwanath. Parts of this paper are also used in Chapter 2 and Chapter 3.

- **Michael Mauderer**, David R. Flatla and Miguel A. Nacenta. Gaze-contingent Manipulation of Color Perception (2016) In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems CHI'16 (10 pages).

This paper is the basis for Chapter 6 and Chapter 7 . The experiments described in this thesis were designed, carried out and analysed by me, with feedback from Miguel Nacenta and Dhanraj Vishwanath. The text, that builds the foundation for this chapter, was written and edited in collaboration with Miguel Nacenta and with feedback from David Flatla. Parts of this paper are also used in Chapter 2 and Chapter 3.

WORKSHOP PAPERS & CONFERENCE ABSTRACTS

- **Michael Mauderer**, Simone Conte, Miguel A. Nacenta and Dhanraj Vishwanath. Using Gaze-Contingent Depth of Field to Facilitate Depth Perception (2014) In i-Perception.

-
- **Michael Mauderer, Simone Conte and Miguel Nacenta.** Utility of Gaze-contingent DOF Blur for Depth Perception (2013) In ITS 2013 Workshop on Visual Adaptation of Interfaces.

In addition to the academic dissemination, the content of this Thesis has also received attention from the press and was mentioned in the following articles.

PRESS

- “New discoveries and enhanced visual experiences through gaze-contingent displays”. cordis.europa.eu¹, sigchi-technews.acm.org², ecnmag.com³
- “St Andrews Team ‘Revolutionise’ 3D Image Viewing”. kingdomfm.co.uk⁴
- “Soon we’ll be able to watch 3D images without the big specs, thanks to St Andrews researchers”. thenational.scot⁵
- “Diseñan una pantalla que reacciona a la mirada del espectador” referion.com⁶
- “La résolution des écrans pilotées par le regard”⁷ techno-science.net

¹http://cordis.europa.eu/news/rcn/124881_en.html

²<http://sigchi-technews.acm.org/archives.cfm?fo=2016-04-apr/apr-05-2016.html>

³<http://www.ecnmag.com/news/2016/03/new-discoveries-and-enhanced-visual-experiences-through-gaze-contingent-displays>

⁴<http://www.kingdomfm.co.uk/news/local-news/st-andrews-team-revolutionise-3d-image-viewing/>

⁵<http://www.thenational.scot/news/soon-well-be-able-to-watch-3d-images-without-the-big-specs-thanks-to-st-andrews-researchers.16903>

⁶<http://www.larazon.es/tecnologia/disenan-una-pantalla-que-reacciona-a-la-mirada-del-espectador-NE12255329>

⁷<http://www.techno-science.net/?onglet=news&news=14947>

FUNDING

This thesis and the research describe herein is supported by the EU's Marie Curie Program: CIG - 303780.

CONTENTS

List of Figures	vii
List of Tables	ix
Listings	x
Acronyms	xi
List of Terms	xiii
1 Introduction	1
1.1 Thesis Statement	3
1.2 Design Space & Scope	3
1.3 Contributions	4
1.3.1 Main Research Contributions	5
1.3.2 Additional Outcomes	6
1.4 Thesis Outline	7
I BACKGROUND & RELATED WORK	9
2 Background	11
2.1 Eye Tracking	11
2.1.1 Important Factors of Eye Tracking	13
2.1.2 The Eyelink 1000	14
2.2 Optics	15
2.2.1 Thin Lens Model	16
2.2.2 Depth of Field	16
2.2.3 Chromatic Aberration	17
2.3 Basics of Visual Perception	17
2.3.1 The Eye(s)	18
2.3.2 The Eye's Movement	22
2.4 Depth Perception	22
2.4.1 Depth cues	22

CONTENTS

2.4.2	<i>Blur as a Depth Cue</i>	23
2.5	<i>Colour Perception</i>	25
2.5.1	<i>Simultaneous Contrast</i>	25
2.5.2	<i>Colour spaces</i>	26
2.5.3	<i>Colour Appearance Models</i>	26
2.5.4	<i>Measures of Colour Difference</i>	27
2.5.5	<i>Testing Colour Differentiation</i>	28
2.5.6	<i>Colour Rendering and Tone Mapping</i>	29
2.6	<i>Statistics</i>	30
2.6.1	<i>Omnibus tests</i>	31
2.6.2	<i>Additional Effect Size Measures</i>	32
2.6.3	<i>Confidence intervals</i>	33
3	<i>Related Work</i>	35
3.1	<i>Scope</i>	35
3.2	<i>Previous classifications</i>	36
3.3	<i>A new way to look at GCDs</i>	39
3.4	<i>Improving Rendering Performance</i>	39
3.4.1	<i>Gaze-contingent Multiresolution Displays</i>	40
3.4.2	<i>Model Based Adaptation</i>	41
3.5	<i>Simulating Visual Phenomena</i>	42
3.5.1	<i>Diagnostic and Perceptual Research</i>	42
3.6	<i>Supporting the User</i>	44
3.6.1	<i>Gaze-contingent Lenses</i>	44
3.6.2	<i>Directing the Observer's Gaze</i>	45
3.6.3	<i>Assisitoe Visual Field Correction</i>	45
3.6.4	<i>HDR</i>	46
3.6.5	<i>DOF</i>	47
3.7	<i>Summary — State of the Art for GCDs</i>	48
II	AUGMENTING DEPTH PERCEPTION	49
4	<i>Simulated Depth of Field</i>	51
4.1	<i>Rendering Gaze-contingent Depth of Field</i>	52
4.2	<i>Experiment</i>	56
4.2.1	<i>Apparatus</i>	56
4.2.2	<i>Software</i>	59
4.2.3	<i>Task and Stimuli</i>	59
4.2.4	<i>Procedure and Experimental Design</i>	60

4.2.5	<i>Measures</i>	62
4.3	<i>Results</i>	62
4.3.1	<i>Absolute Position</i>	64
4.3.2	<i>Depth Difference</i>	65
4.3.3	<i>Unordered Depth Difference</i>	65
4.3.4	<i>Depth Order</i>	67
4.3.5	<i>Individual Differences</i>	67
4.3.6	<i>Meta-Analysis of Correlations between Estimated Depth and Displayed Depth</i>	68
4.4	<i>Discussion</i>	69
4.4.1	<i>Blur and GC DOF Blur's Contribution</i>	69
4.4.2	<i>How Depth from Blur Works</i>	70
4.4.3	<i>Individual Differences</i>	70
4.5	<i>Conclusion</i>	71
5	<i>Simulated Chromatic Aberration</i>	73
5.1	<i>Modelling the Chromatic Aberration of the Human Eye in Blender</i>	75
5.1.1	<i>Assumptions</i>	75
5.1.2	<i>Rendering Chromatic Aberration</i>	76
5.1.3	<i>Colour Abstraction</i>	76
5.1.4	<i>Modelling the Eyes Chromatic aberration</i>	76
5.1.5	<i>Rendering CA in Blender Cycles</i>	77
5.2	<i>Experiment</i>	78
5.2.1	<i>Procedure and Experimental Design</i>	79
5.2.2	<i>Measures</i>	81
5.2.3	<i>Results</i>	81
5.3	<i>Discussion</i>	82
5.3.1	<i>Limitations</i>	83
5.4	<i>Conclusion</i>	83
III	AUGMENTING COLOUR PERCEPTION	85
6	<i>Gaze-contingent Colour Matching</i>	87
6.1	<i>Goals and Research Questions</i>	89
6.2	<i>Common Terminology and GC-Manipulations</i>	90
6.3	<i>Colour Matching Experiment</i>	91
6.3.1	<i>Stimuli & Task</i>	92
6.3.2	<i>Experimental Design & Manipulations</i>	92
6.3.3	<i>Apparatus</i>	94

CONTENTS

6.3.4	<i>Participants</i>	96
6.3.5	<i>Procedure</i>	96
6.3.6	<i>Measures and Statistical Analysis</i>	97
6.3.7	<i>Results</i>	98
6.4	<i>Discussion</i>	102
6.4.1	<i>Limitations</i>	104
6.5	<i>Conclusion</i>	105
7	<i>Gaze-contingent Colour Discrimination</i>	107
7.1	<i>Colour Sorting Experiment</i>	108
7.1.1	<i>Stimuli & Task</i>	109
7.1.2	<i>Techniques</i>	111
7.1.3	<i>Experimental Design</i>	114
7.1.4	<i>Apparatus</i>	114
7.1.5	<i>Participants</i>	116
7.1.6	<i>Procedure</i>	116
7.1.7	<i>Measures and Statistical Analysis</i>	116
7.1.8	<i>Results</i>	117
7.2	<i>Discussion</i>	119
7.3	<i>Conclusion</i>	120
IV	APPLICATIONS & SOFTWARE	121
8	<i>Python Colour Appearance Models</i>	123
8.1	<i>Project Aims</i>	124
8.2	<i>Underlying Technology</i>	125
8.3	<i>Code Design</i>	125
8.4	<i>Code Validation</i>	126
8.5	<i>Usage Example</i>	126
8.5.1	<i>Predicting Perceived Colour - Hunt Model</i>	126
8.5.2	<i>Predicting Large Number of Colours - LLAB</i>	127
8.6	<i>Conclusion</i>	128
9	<i>Gazer — Gaze-contingent Image Viewer</i>	129
9.1	<i>Aims of the Project</i>	130
9.2	<i>Underlying Technology</i>	130
9.3	<i>Code Design</i>	131
9.3.1	<i>.gc File Format</i>	131
9.4	<i>Current Functionality</i>	132
9.4.1	<i>GC DOF</i>	133

9.4.2	<i>GC Colour</i>	135
9.4.3	<i>Presentation Algorithm</i>	136
9.5	<i>Conclusion</i>	136
V	DISCUSSION & CONCLUSION	137
10	<i>Discussion</i>	139
10.1	<i>Summary of Findings</i>	139
10.1.1	<i>Findings on Depth Perception</i>	140
10.1.2	<i>Findings on Colour Perception</i>	140
10.2	<i>Significance of Findings</i>	140
10.2.1	<i>Supporting Depth Perception</i>	141
10.2.2	<i>Supporting Colour Perception</i>	142
10.3	<i>Gaze-contingent Displays revisited</i>	144
10.4	<i>Directions for Research and Open Challenges</i>	147
11	<i>Conclusion</i>	149
11.1	<i>Future Research</i>	151
11.2	<i>Closing Remarks</i>	152
	<i>References</i>	155
VI	APPENDIX	171
Appendix A	<i>Ethical Approval for Research</i>	173
A.1	<i>Letter of approval for studies on gaze-contingent depth perception</i>	174
A.2	<i>Letter of approval for studies on gaze-contingent colour perception</i>	176
Appendix B	<i>Study Material for Experiment on Gaze-contingent Depth of Field</i>	179
B.1	<i>Participant Information Sheet</i>	180
B.2	<i>Participant Consent Form</i>	183
B.3	<i>Demographic Information Questionnaire</i>	187
Appendix C	<i>Study Material for Experiment on Gaze-contingent Chromatic Aberration</i>	189
C.1	<i>Participant Information Sheet</i>	190
C.2	<i>Participant Consent Form</i>	193
C.3	<i>Demographic Information Questionnaire</i>	197
C.4	<i>Post Experiment Questionnaire</i>	199

CONTENTS

Appendix D	Study Material for Experiment on Gaze-contingent Colour Matching	201
D.1	<i>Participant Information Sheet</i>	202
D.2	<i>Participant Consent Form</i>	205
D.3	<i>Debriefing Form</i>	207
D.4	<i>Debriefing Survey</i>	209
D.5	<i>Demographic Information Questionnaire</i>	211
Appendix E	Study Material for Experiment on Gaze-contingent Colour Sorting	215
E.1	<i>Participant Information Sheet</i>	216
E.2	<i>Participant Consent Form</i>	219
E.3	<i>Debriefing Form</i>	221
E.4	<i>Demographic Information Questionnaire</i>	223

LIST OF FIGURES

1.1	Varying surround in a single image.	1
1.2	Schematic of a gaze-contingent System.	2
1.3	Thesis structure	5
2.1	Eye with reflection produced by a light source.	12
2.2	EyeLink 1000 with tower mount.	14
2.3	Schematic of the thin lens model.	15
2.4	Scene captured using an optical systems with limited DOF. . .	16
2.5	Schematic showing varying focal planes for different wave- lengths. Image \textcircled{PD}	17
2.6	Schematic diagram of the human eye.	18
2.7	Normalised human cone response curves.	20
2.8	Relationship between the cone responses and the derived (opponent) colour components.	21
2.9	Example scene showcasing depth cues.	23
2.10	Example photograph that uses a large DOF to make the scene appears smaller.	24
2.11	Simultaneous contrast example.	25
2.12	Sample gradients along the CIELAB axes (relative to D65). . .	27
2.13	Example of the F-M 100-hue-test.	28
2.14	Example scoring of the F-M 100-hue-test	29
3.1	Categorisation of gaze-contingent systems proposed by Duchowski (2002)	36
3.2	Example of images shown with varying resolution.	40
3.3	Example of lines of text presented using moving windows and peripheral masking, as presented in Rayner et al. (2009).	43
3.4	Example of an image displayed with varying luminance. . . .	46
4.1	Example of the stimuli and the underlying depth map.	55
4.2	Example sequence of frames presented during a focus transition.	57
4.3	Overview of the setup used in the GC DOF experiment.	58
4.4	Experimental input device.	59
4.5	Indicated positions Pos_I against actual positions Pos_S in the two background conditions.	64
4.6	Absolute stimulus difference $ Diff_S $ against the absolute indi- cated input difference $I_{ D }$	66
4.7	Blur strength (size of circle of confusion) relative to distance of focal plane. Based on Brooker and Sharkey (2001).	66

LIST OF FIGURES

4.8	Individual performances for depth order discrimination.	68
5.1	An example of purple fringing. Image $\text{\textcircled{P}}$	74
5.2	Example of varying focus in different colour channels	78
5.3	Examples of CA renderings used in the experiment.	79
5.4	Example of CA renderings with varying focus.	80
6.1	Example of local varying gamuts.	89
6.2	Example stimuli from Exp. 1.	92
6.3	Examples of gaze-contingent colour manipulation techniques and interpolation functions.	95
6.4	Plot of the $B_M \times C_C$ interaction on the L^* axis for SC effect.	100
6.5	Plots of the interactions observed for the simultaneous contrast effect in the b^* axis. $B_M \times C_C$ (Left), $C_C \times C_\delta$ (right).	102
6.6	Plots of baseline colour response modulated by C_δ	103
7.1	Example of stimulus setup.	108
7.2	Visualisation of the contrast enhancement function for colour patches.	112
7.3	Examples screen crops from experimental condition GC_{patch}	113
7.4	Examples screen crops from experimental condition GC_{bg}	115
7.5	Example of stimulus setup in S_f condition.	116
7.6	Error scores on the a^* and b^* axis for each technique.	117
9.1	Simplified sequence diagram of Gazer's main loop.	131
9.2	Images showing gazer displaying an photograph taken with the Lytro Illum.	134
9.3	Illustration of the look-up process.	135
9.4	Gazer rendering of a WISE (Wide-field Infrared Survey Ex- plorer) observation data file.	135

LIST OF TABLES

3.1	Overview of the concepts that are used to classify GCDs in other surveys.	37
4.1	Experimental design	62
4.2	Results of the statistical analysis of the experimental measurements. Significant results ($\alpha = .05$) are marked by an asterisk, highly significant results ($\alpha = .01$) by two asterisks.	63
5.1	Results of the post-hoc analysis between CA conditions and baseline using Bonferroni-Holm corrected t-tests.	82
6.1	Results of the repeated measure ANOVA of simultaneous contrast effect in Experiment 1, split by CIELAB axis.	99
6.2	Results of the repeated measure ANOVA of absolute colour appearance, split by CIELAB axis.	101
7.1	Colour Gradients used in the colour sorting experiment and $\Delta_{CIE2000}$ differences between them.	109
7.2	Results of the RM-ANOVAs of error scores in Exp. 2.	118
7.3	Differences in error scores of each technique compared to the baseline technique S_u	119

LISTINGS

4.1	Pseudo code illustrating the mapping from gaze location to frame.	54
4.2	Pseudo code illustrating the mapping from gaze location to frame including a exponential transition function.	56
8.1	Example return value specification for CIECAM02.	125
8.2	Example of how to compute Hunt model predictions.	127
8.3	Example of how to compute LLAB predictions for a large number of input colours.	127
9.1	Example File Structure as JSON	132

ACRONYMS

ANOVA Analysis of variance

CA Chromatic aberration

CAM Colour Appearance Model

CIE International Commission on Illumination

DOF Depth of field

GC Gaze-contingent

GCD Gaze-contingent display

GCMRD Gaze-contingent multi-resolution display

HDR High dynamic range

IR Infra-red

JND Just-noticeable difference

LMS, L-M-S Long-medium-short

RM-ANOVA Repeated measures analysis of variance

SC Simultaneous contrast

SPECIAL TERMS

CIE L*a*b* is a colour space that has a luminance (L*) axis and two chromatic axes that describe colours in terms of red-green (a*) and yellow-blue (b*) components.

CIECAM02 is a standardised colour appearance model that was released by the CIE in 2002.

Depth of Field describes the area of an optical system around the focal plane that can produce a sharp image. Objects outside of this area appear more and more blurred the further they are from the focal plane.

Gaze-contingent display describes the area of an optical system around the focal plane that can produce a sharp image. Objects outside of this area appear more and more blurred the further they are from the focal plane.

Luminance is the relative perceived luminance of colour. Often this is used relative to a specific white point.

Simultaneous contrast is a visual effect wherein the appearance of a colour is influenced by the colour of its surrounding area.

INTRODUCTION

While reading this text what you perceive is determined by contextual factors that you might not be aware of: the medium this text is displayed or printed on and its colour as well as the light illuminating it. Moreover, even though the text is static, as the gaze moves over it, the visual context changes: some words are in the middle of the paragraph surrounded by other words while others are at the edge and surrounded half by empty space to one side. The same holds if you look at the image below (Figure 1.1). Darker shades of green surround some objects in the image,

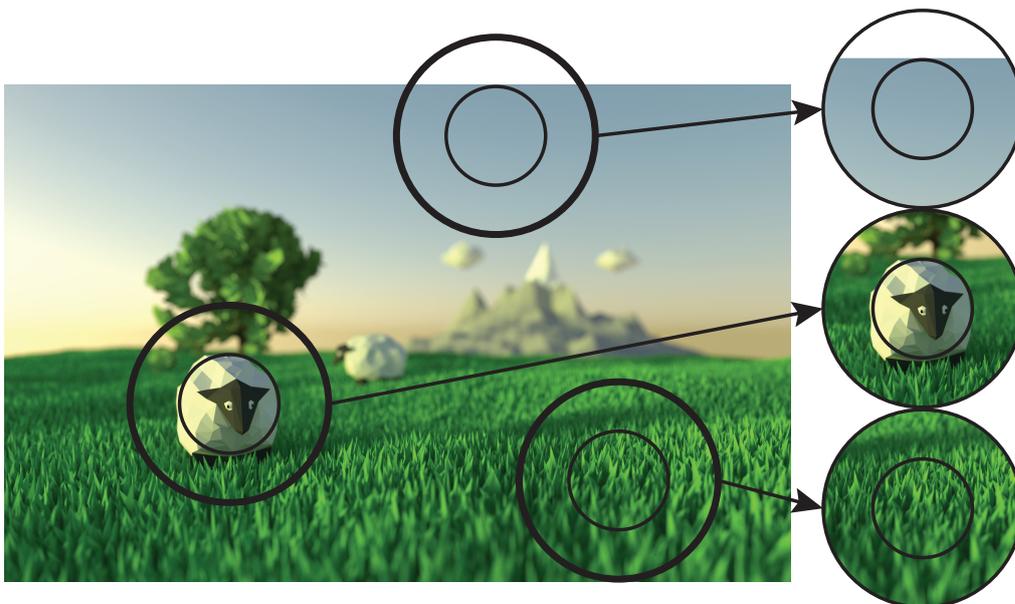


Figure 1.1: In this image different areas have different surround, for example, colour, textures vary between the sky, mountain and the ground area. This can affect how each area is perceived.

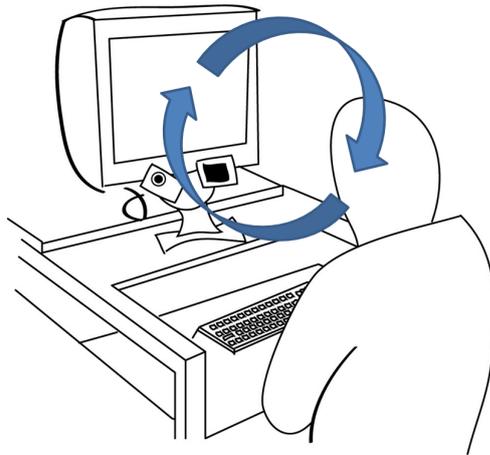


Figure 1.2: Schematic of a gaze-contingent System. The display receives information about the user's gazer and changes its content in response.

others by the blue sky. Busy textures or smooth defocus blur created by the camera's lens surrounds others.

Knowing the visual context of what you see, can be taken into account when presenting information. When photographs are presented, often the background is carefully chosen to make sure the colours in the photograph are perceived as the artist intended. A dark surround might make a bright photo appear even brighter, while a bright surround would make the image appear darker. However, just changing the surround of the whole photograph is a very coarse modification; only the overall image is taken into account, not individual areas of the photo. The presentation is also static and the same regardless of where the viewer is looking. These are natural restrictions of the print medium. But these restrictions do not necessarily exist for digital displays, as we have eye trackers that allow us to determine where someone is looking at any given time. By using this information, we could control the visual context much more fine grained.

This combination of gaze information input and real-time manipulated visual output creates a system called a *gaze-contingent display* (GCD). Such a system creates a direct feedback loop between the observer's perception and the displays presentation of information (see Figure 1.2). It has valuable information about the observer: through the current gaze point on the display, the system exactly knows what is currently perceived, as

well as the visual context of the attended area. The display could then, for example, use this knowledge to leave out colours in the periphery that is not perceived to reduce the computational cost of rendering.

In the past GCDs have been used to research visual perception and create methods to improve rendering performance through gaze-adapted rendering, trying to minimise the information that needs to be computed based on what is actually perceived. However, GCDs might also be able to support the perception of the observer. Through virtually unnoticeable visual adjustments, content can be made more accessible or made to appear more realistic. Thus, gaze-contingent displays can support the observer by making it easier for them to perceive the display content or by providing some form of additional information about the content. For example, by changing the colour or texture around the currently viewed area to make the observed content appear more vivid.

1.1 Thesis Statement

This thesis will investigate the hypothesis that *changing the peripheral display content around the current point of regard can be used to facilitate perception of the main content*. It investigates gaze-contingent techniques that are related to depth and colour perception; two important functions of our visual system and applicable to tasks involving visual perception, for example, navigating virtual environments or reading of colour based information visualisations. It also investigates techniques that aim to enhance the accuracy of depth judgements and help with colour discrimination. Both of these tasks can be measured empirically, thus allowing quantification of the benefits provided by gaze-contingent techniques. The presented investigations will answer the questions of whether we can increase depth judgements and colour discrimination through gaze-contingent techniques and thus show that GCDs can be used to support the observer's perception on a fundamental level.

1.2 Design Space & Scope

Changes to a display can happen on different levels of abstraction. Either on a very low level, that is, pixels and their colour, no matter whether

the represent, text, images or specific objects. On the high-level end of the spectrum, manipulations can happen on a semantic level, taking into account the specific data and objects that are displayed. That could mean highlighting a text block or outlining people in photographs. The manipulations in this thesis will focus on low-level manipulations of colour and texture. These have the advantage that they are not dependent on a specific scenario and can be applied to a wide range of scenarios. For example, manipulating colours applies to any content that is rendered on the display.

GCDs can manipulate the display in a way that is noticed by the observer, by providing, for example, visual annotations on the display wherever one is looking. Alternatively, they can subtly change the content in a way that is not perceived. This thesis focuses on subtle changes on the display which lead to an overall improved impression. These have the advantage that they, from the view of the observer, do not create a specific technique they have to use or learn, but instead they end up creating a display that just has specifically improved properties, like an increased colour gamut.

Since the presented techniques focus on low-level changes targeted at visual perception, their effects will be investigated using empirical methods from perceptual psychology. The investigations are designed to provide quantitative empirical evidence through psychophysical studies, that is, controlled lab experiments. The equipment used will be research equipment for the experiments, not off-the-shelf hardware, as this allows for higher precision measurements and more precise manipulations of the display content, which in turn leads to higher confidence in the experimental results.

1.3 Contributions

This thesis contributes to the understanding of gaze-contingent displays, how they can be utilised to facilitate tasks and how they can affect visual perception in general. The presented investigations provide empirical results that lay the foundation for future investigations and development of gaze-contingent technologies, as well as general applications of colour and depth perception.

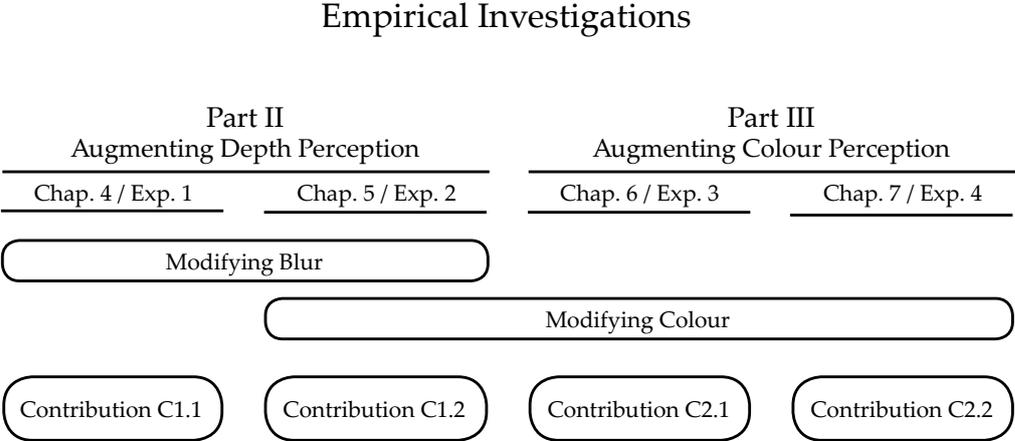


Figure 1.3: Overview of the structure of this thesis, including empirical investigations, their main approach and contribution.

1.3.1 Main Research Contributions

The main contributions of this thesis consist of the results of empirical evaluations of gaze-contingent techniques with two aims (see Figure 1.3 for an overview). The first two techniques aim at improving depth discrimination and distance judgement. The second two techniques affect the perception of colour with the aim to extending the perceived colour gamut of displays and facilitating colour discrimination. All of these techniques promote the idea of facilitating perception and show how we can exploit GCDs for the benefit of the observer. Explicitly the main contributions are:

C1.1: Empirical evidence that depth perception can be augmented with gaze-contingent depth of field (GC DOF)

This thesis presents the results of an empirical investigation of an existing technique to create gaze-contingent depth of field. The results are the first quantitative results on how GC DOF affects depth perception and validate that it does provide a benefit to depth perception.

C1.2: Empirical data on the influence of gaze-contingent chromatic aberration (GC CA) on depth perception

This thesis expands on the GC DOF technique adding more optical faithfulness by simulating additional properties of the lens system of the human eye. It presents a technique that allows the creation of CA based on optical models and the results of an experimental investigation which indicate that the effect of gaze-contingent GC CA might be too small for most practical uses.

C2.1: Gaze-contingent techniques that aim to influence colour perception empirical data on their effect

This thesis presents novel gaze-contingent techniques that manipulate the perception of the observer through simultaneous contrast. It also present data from an empirical evaluation that shows how these manipulations change the perception of colour in a colour matching experiment.

C2.2: Empirical data on how gaze-contingent colour manipulations can be used to increase colour discrimination

Following on from the previous results this thesis shows how gaze-contingent colour manipulations can be used to facilitate a colour sorting task, and it provides evidence that doing this can increase the observer's ability to discriminate between similar colours.

1.3.2 Additional Outcomes

In addition to the main contributions, this thesis contains smaller research outcomes described in the following sections.

C3.1: A current overview of the state of the art of GCDs

This thesis provides a review of the literature on GCDs at the time of this writing and a classification of the existing GCDs according to their interaction with the human visual system and how the benefit is derived from it, that is, whether the system aims to reduce computational effort or facilitate cognition or perception.

C3.2: A software implementation of colour appearance models

Colour appearance models (CAMs) played a large role in the initial investigation of gaze-contingent colour manipulations and are required for their further development. The colour-science package¹ provides an easy to use Python implementation of these models. The CAMS included in colour-science have been developed as part of this thesis and are now available to the public.

C3.3: An application for displaying light field images using off-the-shelf eye tracking

To allow the end user to see the benefits of GC DOF first hand, there is an application (Gazer) that uses commercial hardware to generate and display scenes with GC DOF. Gazer is released as an open source project and freely available². Gazer is not limited to DOF based images. It can easily be extended to allow other gaze-contingent rendering algorithms, for example, colour based approaches. This thesis presents one such example showing how high dynamic range astronomical images can be displayed using gaze-contingent rendering. Gazer serves to demonstrate that the results from the lab studies in this thesis can be applied to real-world use cases.

1.4 Thesis Outline

This thesis consists overall of five parts, each in turn consisting of multiple chapters. The first part is 'Part I: Background & Related Work', which gives a general overview of the background and related work of the thesis. It consists of 'Chapter 2: Background', which gives an overview of the topics of visual perception with a focus on depth and colour perception. This chapter provides the relevant information required for the understanding of the techniques developed and experiments performed in the rest of the thesis. This chapter is followed by 'Chapter 3: Related Work', which provides an overview of related work from the area of GCDs. It describes the state of the art of GCDs and provides context for this thesis.

¹<http://colour-science.org/>

²<https://github.com/MichaelMauderer/Gazer>

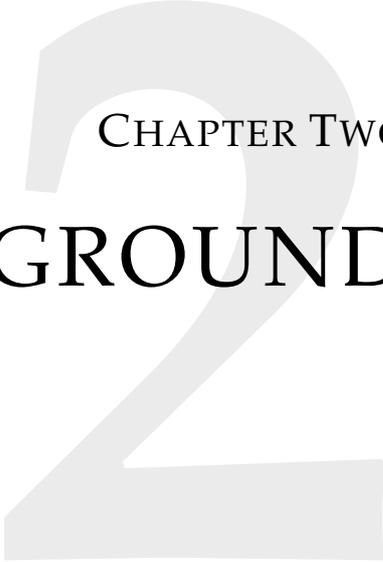
The second part of the thesis ‘Part II: Augmenting Depth Perception’ presents research on how depth perception can be enhanced through the gaze-contingent presentation of images. The first chapter ‘Chapter 4: Simulated Depth of Field’ contains an evaluation of an empirical experiment that investigates the benefits of simulating depth of field and how it affects depth perception. In the following chapter ‘Chapter 5: Simulated Chromatic Aberration’ the concept of GC DOF is extended by simulating the optical effect of chromatic aberration. The chapter presents an approach to artificially create images containing CA and an empirical investigation of its effect on depth perception.

The third part ‘Part III: Augmenting Colour Perception’ presents research on how gaze-contingent displays can be used to affect colour perception. Its first chapter ‘Chapter 6: Gaze-contingent Colour Matching’ presents a first technique based on simultaneous contrast and an empirical investigation shows whether this technique can influence the perception of colour. Building on the initial insights the chapter ‘Chapter 7: Gaze-contingent Colour Discrimination’ presents an investigation that applies the presented techniques to a specific task, namely sorting of colours. These results give insights into the abilities of the observer to discriminate very similar looking colours and show how the gaze-contingent manipulations can aid their discrimination ability.

The last part ‘Part V: Discussion & Conclusion’ discusses and summarises the findings of the previous parts and provides an overview of their significance in the context of this thesis. The chapter ‘Chapter 10: Discussion’ summarises the results of the chapters and show their relevance for the overall thesis questions. The last chapter ‘Chapter 11: Conclusion’ summarises the presented work, points out the significance and shows potential future direction and follow up work that can be undertaken based on the findings of this thesis.

PART I

BACKGROUND &
RELATED WORK



CHAPTER TWO

BACKGROUND

This chapter gives a general background on eye tracking and visual perception. Eye tracking technology is one of the basic building blocks of gaze-contingent displays, which are a fundamental technology used in this thesis. The description of eye tracking is followed by a basic introduction to aspects of depth perception and colour vision which are important for Part II and Part III of this thesis.

2.1 Eye Tracking

Eye tracking technology allows us to determine where a person is looking. This is valuable information that gives us insight into the observers current perception. It is therefore a popular technology that is used in research on visual perception and marketing, but can also be used to create systems that use gaze as an input modality (Duchowski, 2002).

Over the course of its history, eye tracking technology has taken on many forms, from attaching objects to the eye ball (Wade and Tatler, 2009; Robinson, 1963) to modern remote eye-tracking systems based on video observation of the eyes (Young and Sheena, 1975). The research presented in this thesis was conducted with optical IR corneal reflection tracking. This type of eye tracking is non-intrusive, accurate and easy to use.

Pupil-corneal reflection based eye tracking uses a (near) infra-red (IR) light source and an (IR) camera. The light source is positioned in a way that the camera can detect a reflection in the cornea. Image recognition is

2. BACKGROUND

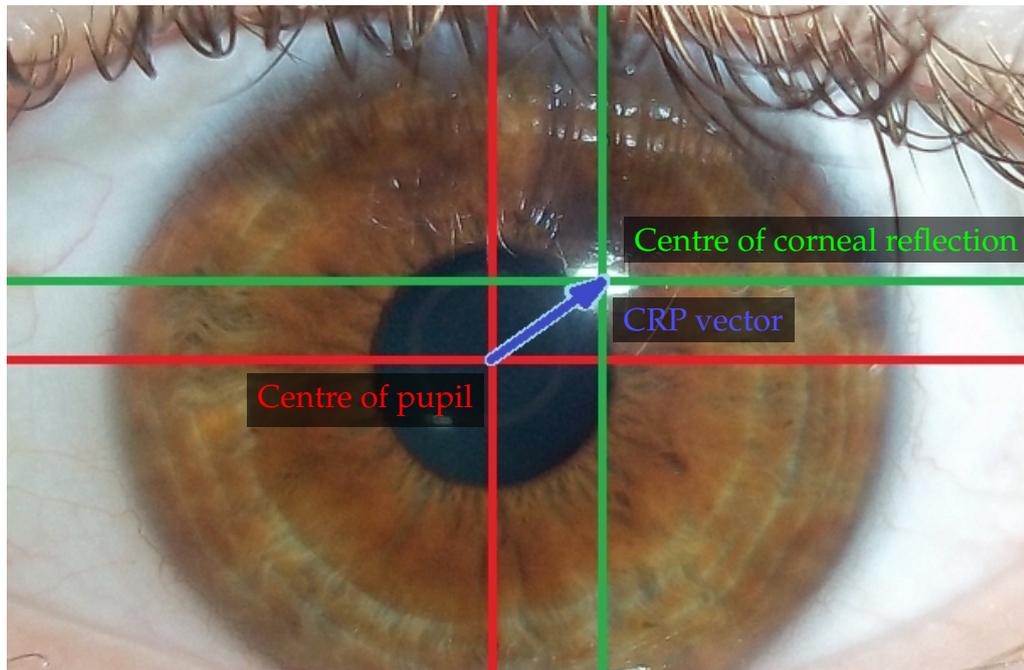


Figure 2.1: Eye with reflection produced by a light source. The red cross indicates the centre of the pupil, the green cross the centre of the reflection. The resulting CRP (Corneal-Reflection->Pupil) vector between the two (blue) can be used to determine the gaze direction. © Author: Z22. Derivative work of the above file created by Björn Markmann.

typically used to detect the darkest part of the image (the pupil) and the brightest part of the image (the reflection) (Morimoto and Mimica, 2005). See Figure 2.1 for an example image of what such an image of the eye captured by an eye tracker could look like.

The vector between the centre of the pupil and the corneal reflection will change with the movement of the eye and can be mapped to positions on the screen. To create the mapping between vector and screen coordinates typically a calibration procedure is used, in which a number (usually 5-12) points are displayed on the screen, and the resulting vector is recorded (Morimoto and Mimica, 2005). This approach is robust against small head movements, but the quality of the calibration deteriorates, the further the head moves from its calibration position (Morimoto and Mimica, 2005).

2.1.1 Important Factors of Eye Tracking

Several factors determine the quality of an eye tracker and in turn what it can be used for. For example reading studies might have different requirements than large display gaze interactions.

Accuracy describes how well aligned the data of the eye tracker is with reality. In general, eye trackers try to measure the position and rotation of the eye and from there infer one the point on the display that the eye is pointing to. The accuracy can be measured as the maximum offset between the point on the display that is reported by the eye tracker and the point that the eye is actually pointing to. The difference between the two is given as angular distance in degrees to give a measurement that is independent of the display distance. Modern research grade eye trackers can achieve a nominal accuracy of up to 0.5 degree^{1 2}.

Temporal resolution indicates how many samples per second the eye tracker can deliver. This depends on how fast the eye tracking can gather and process data. The higher the sampling rate, the more accurate fine movements in the eye can be determined. Values range from 30Hz³ to 2000Hz⁴.

Latency describes the delay between eye movement and event and registration in the end user application. This accounts for processing time, including image and signal processing. Ideally, this value should be as low as possible. Nominal values for existing eye tracking systems vary between 2 ms⁵ and 50 ms⁶

Robustness describes the change of accuracy over time. Eye tracking accuracy can deteriorate due to environmental changes, for example, changes in lighting, but also changes of the eye position in relation to the eye tracker. This means that especially outdoors settings can be challenging for video-based eye trackers due to high-level variance in the surround illumination and movement of the observer (Morimoto and

¹http://www.sr-research.com/el1000plus_baseunit.html

²<http://www.tobiiipro.com/product-listing/tobii-pro-tx300/>

³<http://www.tobiiipro.com/product-listing/tobii-pro-x2-30/>

⁴http://www.sr-research.com/el1000plus_baseunit.html

⁵http://www.sr-research.com/el1000plus_baseunit.html

⁶<http://www.tobiiipro.com/product-listing/tobii-pro-x2-30/>



Figure 2.2: EyeLink 1000 with tower mount. The light source and camera are positioned outside of the field of view of the user by using an IR mirror.

Mimica, 2005). A standard solution for these problems is to perform eye tracking in closed rooms with constant illumination and use chin-rests to stabilise the tracked person's head.

2.1.2 The EyeLink 1000

All of the experiments described in this thesis are performed with an EyeLink 1000⁷ using a tower mount configuration (see Figure 2.2). It provides data at a nominal rate of 1000 Hz at an accuracy of <1 degree and with a latency of 1.4 ms. The tower mount provides a chin-rest that allows for long-term accuracy as it stabilises the head position.

⁷http://www.sr-research.com/el1000plus_baseunit.html

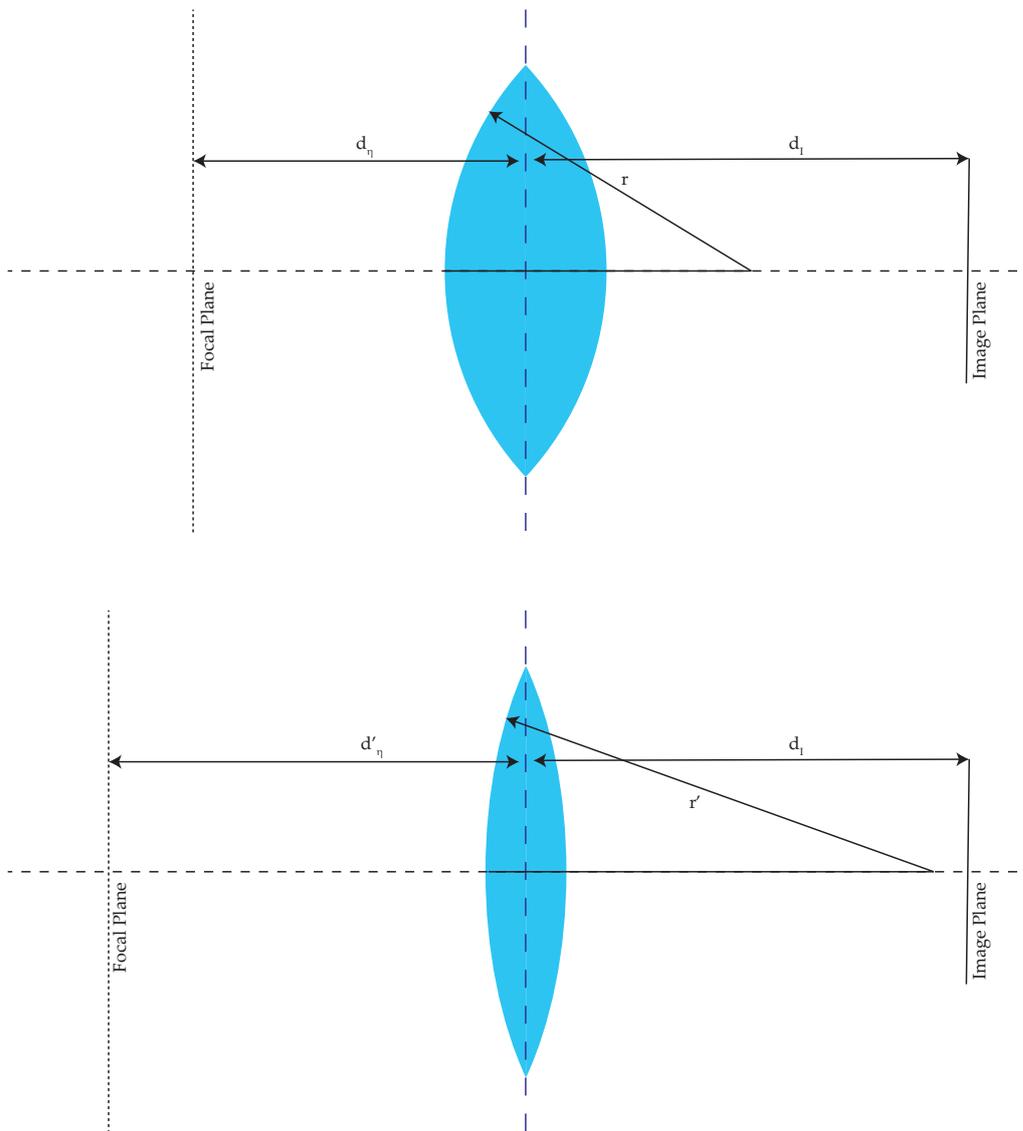


Figure 2.3: Schematic of the thin lens model. The upper image shows a lens with a smaller radius and closer focal plane. The lower image, a larger radius and a more distant focal plane.

2.2 Optics

This section describes the basics of the thin lens model. These help to understand the properties of the eye's lens, how depth of field works, and what chromatic aberration is.

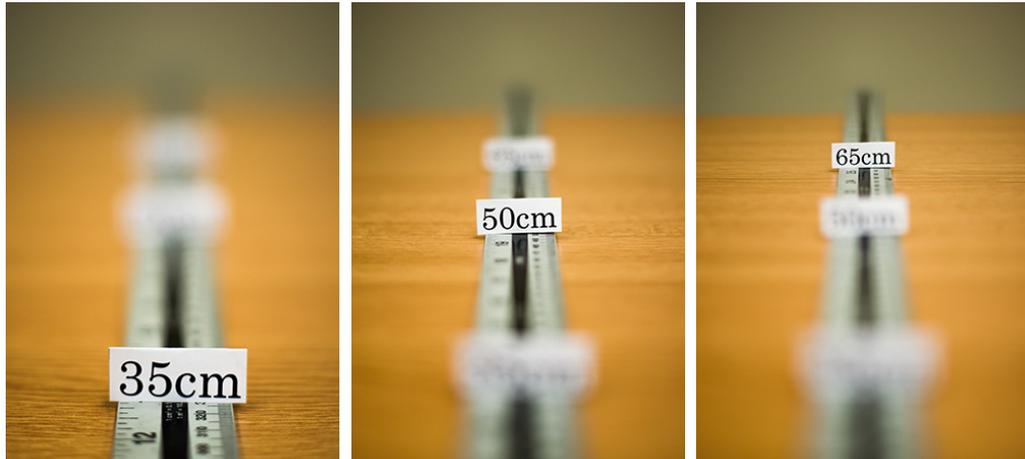


Figure 2.4: Scene captured using an optical systems with limited DOF focused on different distances showing the resulting defocus blur. Images © Michael Mauderer.

2.2.1 Thin Lens Model

A lens system can be abstracted as a single thin lens system. Using this model the focus planes light passing through the lens (see Figure 2.3) can be computed using the *thin lens equation*. The thin lens equation relating the refractive index n_λ for a given wavelength λ , curvature r of the lens and distance of the image plane d_I and resulting distance of the resulting focal plane d_λ is given as

$$\frac{1}{d_I} + \frac{1}{d_\lambda} = \frac{(n_\lambda - 1)}{r} \quad (2.1)$$

2.2.2 Depth of Field

Usually, the image plane is located at a fixed distance from the lens. Thus objects that are not located at the exact distance of the focal plane are not projected as a single point onto the image plane. Instead, the light bundle will be spread out over an area called *circle of confusion*, resulting in blurring the object. The amount of blur varies with the distance of the object from the focal plane (see Figure 2.4).

Optical systems can change the focal plane, by either changing the distance between image plane and lens (common for mechanical imaging systems) or by changing the curvature of the lens (common for biological imaging systems like the human eye).

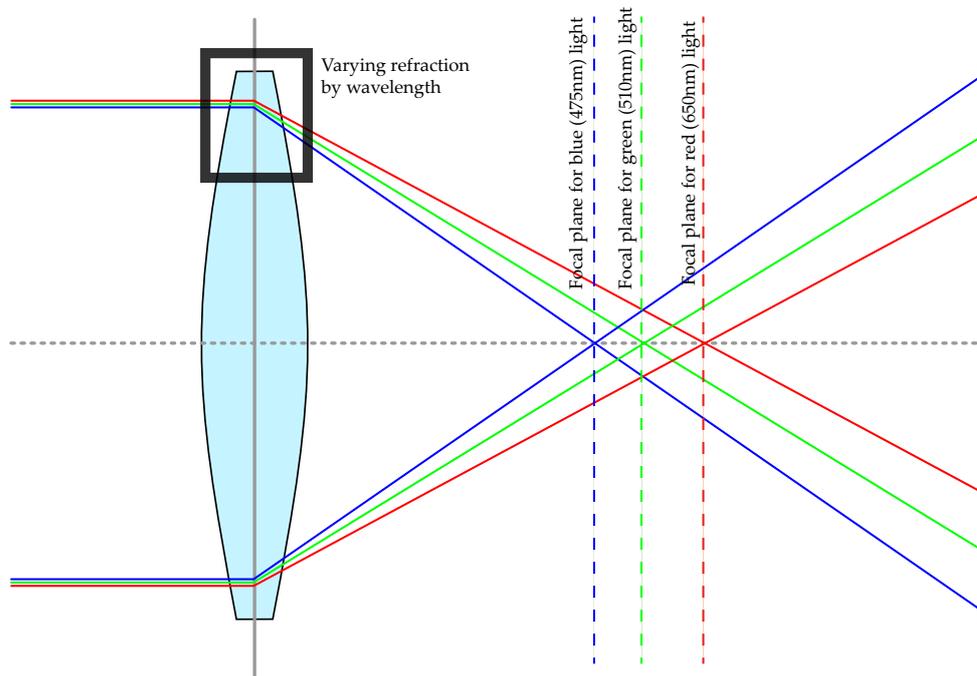


Figure 2.5: Schematic showing varying focal planes for different wavelengths. Image .

2.2.3 Chromatic Aberration

As described in the previous section, light gets focused through a lens, and the focal plane depends on the lens and image plane (see further down for detailed equations). However, this is a slight simplification as not all light gets focused equally by a lens. The refractive index of an optical medium depends on the wavelength of the light, and thus light of an object in different wavelengths gets focused at different points (see Figure 2.5 for a schematic overview. This kind of chromatic aberration is called axial chromatic aberration, as the focus point varies along the optical axis. This is opposed to transverse chromatic aberration in which the image planes are focused equally, but transposed, that is, the images are not perfectly aligned.

2.3 Basics of Visual Perception

Vision provides us with information about the space around us: the spatial relation of objects to ourselves as well as information like colour

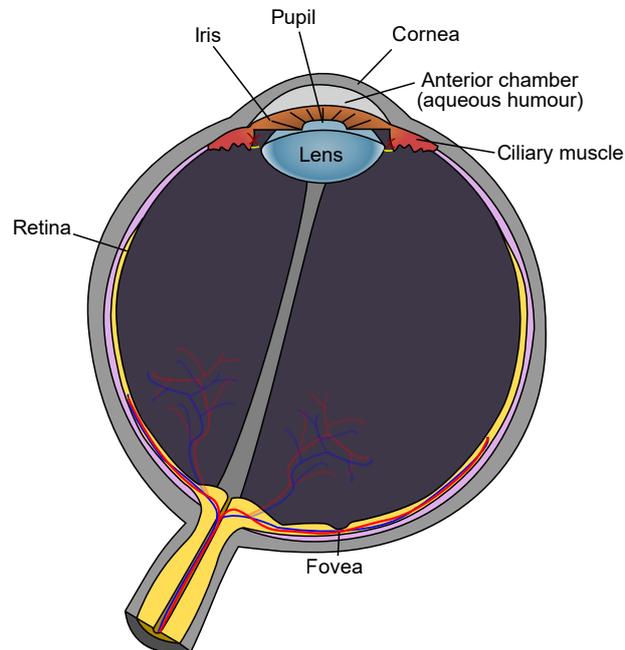


Figure 2.6: Schematic diagram of the human eye, showing the different parts of the lens system. Author: Rhcastilhos, ©

and texture that allows us to identify objects.

To see the eyes act as sensors that gather external information: they measure the incoming light. This information is then further processed by the visual system to create an internal representation of the environment. The following sections will give an overview of the structure and properties of the eye and the processing of the visual signals, especially with regard to colour and depth information.

2.3.1 The Eye(s)

The eyes are the sensors that gather the information the light provides. The properties of human vision are directly tied to the physical structure of the eyes, for example, colour vision through light-sensitive cells in the retina and depth sensing through the disparity information the eyes provide. At its core, a single eye can be described as an optical lens system and a sensor.

2.3.1.1 The Eyes' Lens System — Optical Properties

Light enters the eye through the pupil and gets focused by its cornea and lens on the retina. While the cornea accounts for most of the eyes focusing power, the lens is variable and can change its shape to focus at different distances. This process is called accommodation (Wang and Ciuffreda, 2006). The eye also exhibits a limited depth of field that is blurriness away from the plane of focus, which is affected by the size of the pupil opening (Wang and Ciuffreda, 2006).

On its way to the retina, the light has to pass through optical media, for example, the cornea, lens but also the aqueous humour (see Figure 2.6 for a schematic overview). All of these layers can affect the light, and introduce optical aberrations and distortions, for example, visible shadows through floaters (Murakami et al., 1983) or colour fringes at contrast boundaries due to chromatic aberration (Thibos et al., 1992; Atchison and Smith, 2005)).

2.3.1.2 Chromatic Aberration in the Eye

CA is of special interest for visual perception since it could affect the accuracy of vision (Hartridge, 1918), colour perception (Fry and Somers, 1974) and accommodation behaviour (Charman and Tucker, 1978). Atchison and Smith (2005); Campbell et al. (1999); Howarth et al. (1988); Ogboso and Bedell (1987) thus have investigated the optical properties of the human eye and measured the refractive indices of the eye and estimate the resulting CA through models and simulations.

Chromatic aberration is closely related to defocus blur. CA in the eye is dependent on the accommodation state and thus can contain information about distance. Sanson et al. (2012) have shown that CA can play a role in the perceptual system in jumping spiders. For humans there are optical illusions based on colours that induce the perception of depth and Winn et al. (1995) propose that these could be based on CA-based depth perception. In addition to the perceptual evidence, a computer vision approach from Garcia et al. (2000) uses CA to extract depth information from still images, which shows that CA does indeed contain information about depth.

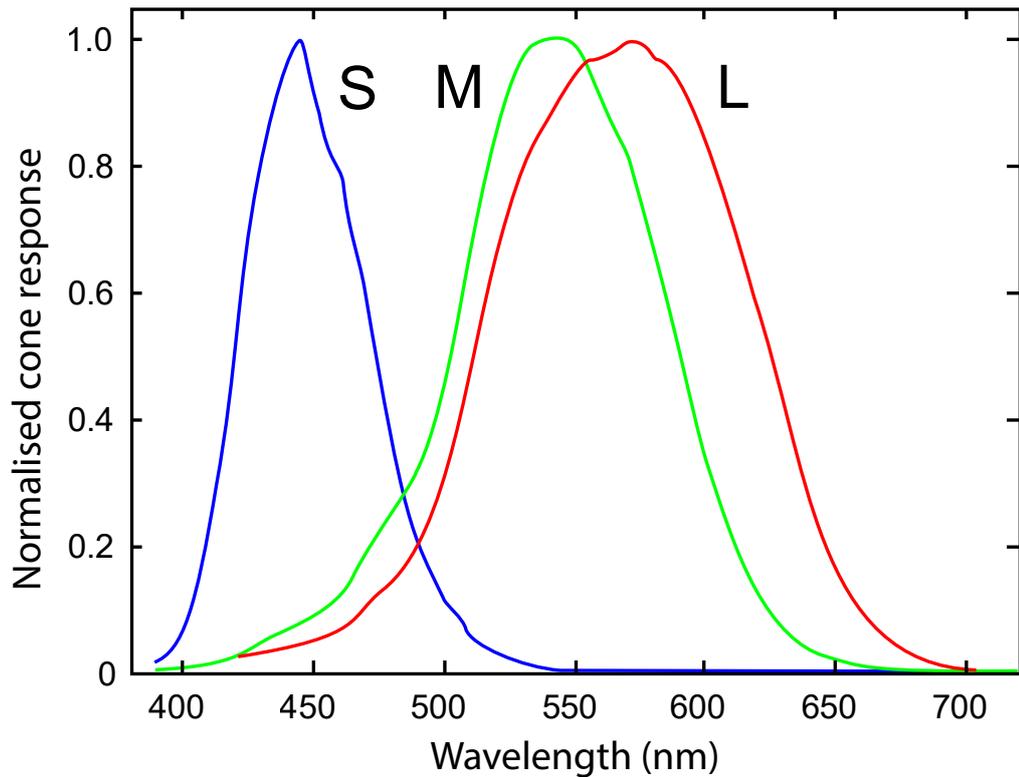


Figure 2.7: Normalised human cone response curves for short (S), medium (M) and long (L) cones. Each cone has varying sensitivity to different wavelengths and creates a different response. Author: Vanessa Ezekowitz , 

2.3.1.3 The Eyes' Sensor – The Retina

The retina is the sensor that gathers the incoming light for further processing in the visual system. It is made up of a variety of light-sensitive cells, typically rods and three types of cones that are each sensitive to specific spectra of light (see Figure 2.7 for a sensitivity diagram of the cones) (Stockman et al., 1993). Rods serve to see in low light levels while the three types of cones allow us to differentiate between the different wavelength of incoming light at normal light levels, enabling the perception of colour.

Rods and cones are not uniformly distributed throughout the retina. Rods are mostly found in the periphery of the retina, while cones are most dense in the *fovea*. Further out in the periphery the density of rods reduces and image information is, therefore, coarser (Curcio et al., 1987). There also exists an area in the retina which does not have any rod or cones at all: the blind spot. While no information is available there, the perceptual

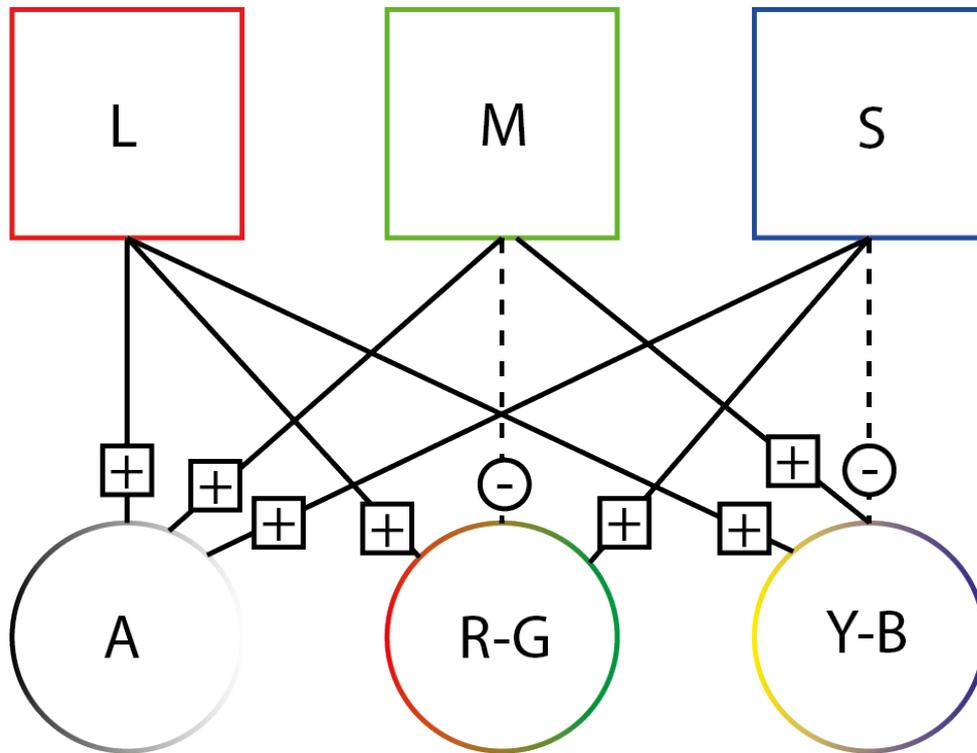


Figure 2.8: This diagram shows the relationship between the cone responses and the derived (opponent) colour components. The L, M and S signals get converted into an achromatic luminance signal (A) and two opponent colour signals (red-green R-G and yellow-blue Y-B). The sign of the contributions of each cone (positive or negative) are noted at the corresponding edges.

system fills in information that falls into this area (Cumming and Friend, 1980).

After the rods convert the incoming light into a signal consisting of three components (long, medium and short, LMS) the next step of processing in the retina happens by converting the LMS signal into two opponent colours and a brightness signal (Figure 2.8). The opponent colours are derived from the L-M cones, resulting in a red-green signal and the L-M-S cones resulting in a yellow-blue signal. These encoded signals are then further processed in the remaining part of the visual system (Fairchild, 2013).

2.3.2 The Eye's Movement

Eye movement generally consists of phases of relative stillness called *fixation* where the gaze is maintained at a specific location inside of the visual field and *saccades* which consist of rapid eye movement between the fixation locations. In addition to these two modes of operation, the eyes also have the ability to track a moving object in the visual field, which results in an eye movement pattern called *smooth pursuit*.

During a fixation the area of interest is projected onto the retina, resulting in a clear image with the highest perceptible resolution. Even while maintaining a fixation, the eye is not completely still and some movements (<12 arcminutes Collewijn and Kowler (2008)) called microsaccades occur. During a fixation, the visual system takes in the sensory information that will result in visual percepts.

Switching the location of a fixation happens through a saccade. Saccades are characterised by a fast ballistic eye movement. The target of the saccade is determined before it starts, and the trajectory cannot be changed while it is underway. During a saccade, the eye is effectively blind. This property is especially of interest for gaze-contingent displays, that try to hide changes from the observer, since changes performed before a fixation starts will be imperceptible to the observer.

2.4 Depth Perception

This section describes some of the basic properties of depth perception, with a special focus on the role of depth of field blur, which will be used in Part III for gaze-contingent manipulations.

2.4.1 Depth cues

Depth information is inferred from multiple sources of information. Multiple *depth cues* are aggregated to get a more accurate estimate of depth than a single source could provide. Some depth cues are monocular, they are derived from information that can be gathered by a single eye and be represented in flat 2D images, for example, the relative or expected size of objects and where in the field of view objects are located (Cutting

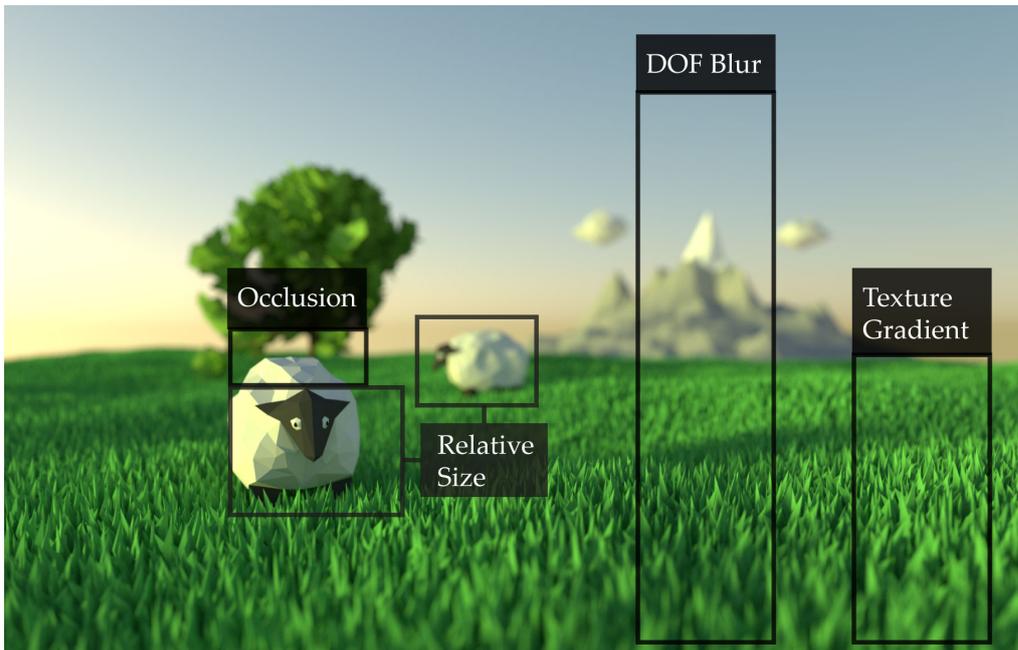


Figure 2.9: Example scene showcasing depth cues, for example, texture gradients, occlusion, relative size and DOF blur.

and Vishton, 1995). These depth cues are also commonly used in pictorial depictions of scenes that show a three-dimensional space and allow the viewer to determine spatial relations (see Figure 2.9).

Sometimes even the existence or absence of specific depth cues can already influence the perceived depth, which can be seen in tilt-shift photography, where the use of strong DOF lets scenes appear like miniature versions of the depicted scene (Vishwanath and Blaser, 2010) (see Figure 2.10 for example).

2.4.2 Blur as a Depth Cue

Of special note for this thesis is the depth information that can be derived from the limited DOF of the eye. When we look at an object, the eye's lens focuses on this object and other objects located at different depths can appear blurred. Objects appear more or less blurred depending on their position, and the position of the focal plane (Kolb et al., 1995; Potmesil and Chakravarty, 1981). Blur patterns can affect the perceived distance between objects (Mather, 1997) and convey information about the distance of the focused object from the observer (Vishwanath and Blaser, 2010).

2. BACKGROUND



Figure 2.10: Example photograph that uses a large DOF to make the scene appears smaller, like a miniature or model version. Photo by Leandro Neumann Ciuffo ©

Research from visual perception that investigates the role of blur for depth perception uses mostly static images and textures with blur. Marshall et al. (1996); Mather (1996); Mather and Smith (2002); O’Shea et al. (1997) have shown that relative blur differences affect the judgement of ordinal depth but not quantitative depth. However, Nefs (2012); Mather (1996); Wang et al. (2011); Watt et al. (2005) have also shown that the presence of blur can also alter quantitative depth perceived on the basis of other cues such as perspective or binocular disparity.

Newer research suggests that the overall pattern of blur created by DOF is a quantitative cue for perceived egocentric distance (Vishwanath and Blaser, 2010) and perceived size of objects (Held et al., 2010). The egocentric distance information provided by defocus blur may also serve to scale other depth cues (Vishwanath and Blaser, 2010). Finally, blur can contribute to speed and accuracy in depth perception (Mather and Smith, 2004) and in some situations, blur differences between objects separated in depth are more discriminable than binocular disparity between them (Held et al., 2012).

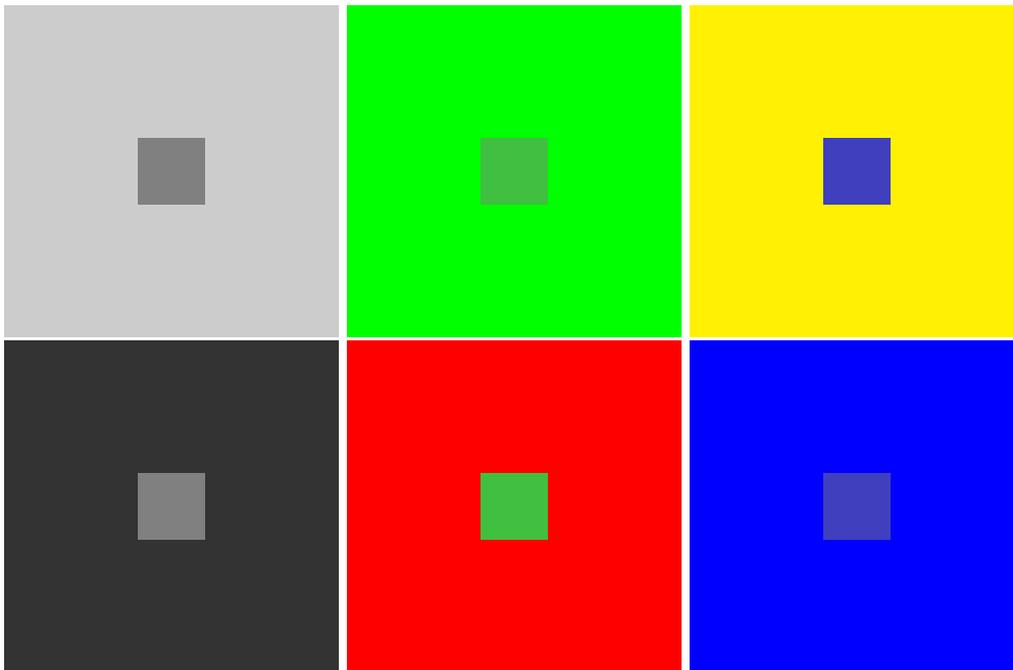


Figure 2.11: Example of simultaneous contrast. The central patches in the top row contain the same colour as the patches of the bottom row but are perceived differently (in chromaticity and lightness) due to their surround.

2.5 Colour Perception

The perception of colour arises from the signals created in the retina. This section provides basic information on colour perception, simultaneous contrast, and the CIE $L^*a^*b^*$ colour space that is used to describe colours.

While the initial processing of the incoming light information in the retina is described above, the following sections will give a short high-level overview of some of the additional factors that play a role in the perception of colour. Additional information on this topic can be found in more comprehensive works, for example, Fairchild (2013).

2.5.1 Simultaneous Contrast

Central to work on the manipulation of colour perception is the effect of simultaneous contrast (SC). SC refers to how the appearance of a colour patch is often influenced by the colour that surrounds it. This effect can be seen in Figure 2.11. The shifts in colour that are observed follow opponent colour dimensions, for example, dark surround makes colour

appear brighter; reddish surround makes colour appear greener. The basics of CA have been explored using colour matching experiments in which participants compare patches of colours surrounded by different colours. (e.g., Blackwell and Buchsbaum (1988); Jameson and Hurvich (1961)). Newer developments focus on creating computational vision models that can predict the appearance of colours affected by SC even with more complex surrounds (Blakeslee and McCourt, 1999).

2.5.2 Colour spaces

Colour perception research requires precise ways to describe colours. This is typically done by using *colour spaces* which are multidimensional coordinate spaces in which each dimension describes an aspect of the colour. Absolute colour is often described in the CIE XYZ space. Colours in this space can be computed from physical spectra through *observer functions*, which are based on the cone sensitivities of the eyes to derive a coordinate for the perceived colour of an average human observer (Smith and Guild, 1931). The XYZ space is then often used as a basis for further transformation of specific purpose colour spaces.

Colour spaces in devices that reproduce colours through light emission (e.g., displays) are often based on red, green and blue (RGB), as these colours can be linearly combined to create a wide range of colours in display devices. For a specific device, the range of colours that can be reproduced is called its *gamut*.

This thesis also makes use of the 1976 CIE $L^*a^*b^*$ colour space (CIELAB) (Robertson, 1977, 1990) because it is based on opponent colour channels (Fairchild, 2013; Goldstein, 2013) which are closely related to simultaneous contrast effects (Fairchild, 2013). CIELAB describes colours using lightness (L^* : dark to bright), a a^* axis (green to red), and a b^* axis (blue to yellow), as shown in Figure 2.12.

2.5.3 Colour Appearance Models

SC and other colour perception phenomena are described in Colour Appearance Models (CAMs) that predict the appearance of a colour given extrinsic viewing conditions, for example, the surround illu-

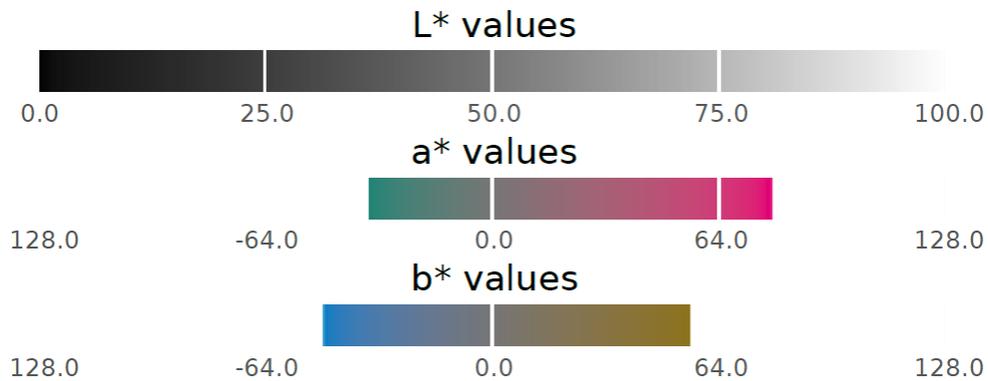


Figure 2.12: Sample gradients along the CIELAB axes (relative to D65). The L^* gradient assumes $a^* = b^* = 0$, the a^* and b^* gradients assume $L^* = 50$ and $a^* = 0$ or $b^* = 0$ respectively. colours are truncated to sRGB.

mination (Fairchild, 2013). A range of CAMs exist, including the application-oriented CIECAM02 (Moroney et al., 2002), the comprehensive Hunt’s model (Hunt, 1987, 1994), and other recent computational approaches (Otazu et al., 2012). These CAMs assume static viewing conditions (e.g., constant light, no changes in colour during viewing), so they might not generalise to the temporally-dynamic conditions of gaze-contingent colour manipulations.

2.5.4 Measures of Colour Difference

Several measures and systems have been developed to describe the perceived difference between colours. The Munsell colour systems (Munsell, 1950) was designed to be perceptually uniform along each of its axes. This means that each step is observed as equally large and perceptual differences are linear along each axis. Munsell colour system is based on experimental data for discrete colour patches, which means that the Munsell system does not provide a continuous colour space, but only discrete empirical data points for specific physical objects viewed under specific light conditions (Nickerson, 1940).

A more generalisable approach was taken when designing CIELAB, which was also designed to be perceptually uniform (Robertson, 1977), meaning that the Euclidean distance could be used as a simple measure of colour difference. This measure of perceived difference is called ΔE , and for the Euclidean distance, it was determined that a value of about 2.3

2. BACKGROUND

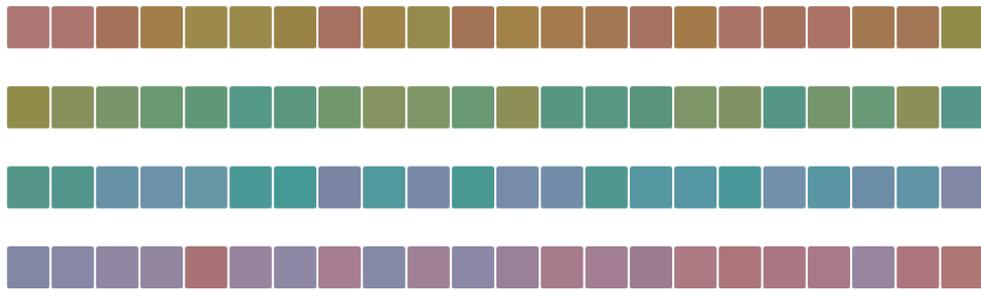


Figure 2.13: Example of three rows of colour patches used in a F-M 100-hue-test. The first and last patch in each row is fixed, while other patches can be re-arranged within the row. The goal is to create smooth gradients.

corresponds to a just-noticeable difference (JND). To further improve the uniformity of ΔE across CIELAB and compensate for interactions between hue/chroma/lightness and other perceptual effects, iterative modification where proposed Robertson (1990), the latest of which is $\Delta_{CIE2000}$, which will be used in the remainder of this chapter to describe colour differences.

2.5.5 Testing Colour Differentiation

The Farnsworth-Munsell 100-Hue and Dichotomous Tests for Color Vision (F-M 100-hue-test) (Farnsworth, 1943) is test that can determine a person's ability to differentiate colours. It can detect different kinds of colour vision deficiencies like deuteranopia (red-green colour deficiency) but is not limited to specific types like for example the Ishihara test which test only for specific types of colour vision deficiency. It consists of multiple rows of gradients of colours that are shuffled and need to be sorted by the participant (see Figure 2.13).

The final order of the colour plates is scored to determine how well colours in a specific range can be discriminated. From this, it is possible to determine colour vision deficiencies in an observer for specific colours. A simple way to score a gradient is to assign each patch a number according to its actual position along the gradient. For each patch, in the participant-determined order, the absolute difference of the patch's number and the numbers of the patches on its left and right is calculated and then summed

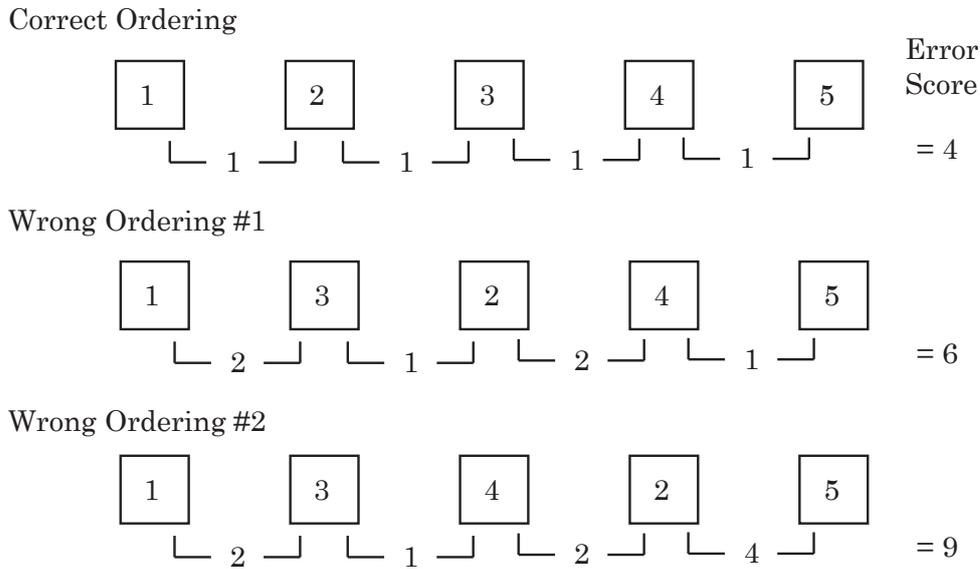


Figure 2.14: Example scoring of the F-M 100-hue-test with a 5 patch arrangements. Each row patch contains its correct position. The number between each patch pair indicates the error score for derived from the positions.

the sub-scores for all patches. See Figure 2.14 for an example scoring.

2.5.6 Colour Rendering and Tone Mapping

Colour perception plays an important role in the development of computer graphics (Bartz et al., 2008), interfaces (Kindlmann et al., 2002), information visualisations (Flatla and Gutwin, 2010; Spence et al., 1999), and image compression algorithms (Skodras et al., 2001; Wallace, 1991). *Tone mapping* and *gaze-contingent displays* that manipulate colours are of particular importance to the work in this chapter.

Different media have varying capabilities to display colours, for example, limited by the print colours available or the light a display can emit. When displaying images on different media, a process called *tone mapping* is used to transform the colours of an image so that they can be displayed or printed on the target device. For example, images from a camera with a wide colour gamut and high dynamic range (HDR) sensors can be transformed to the gamut of a low dynamic range display with a smaller colour gamut (Reinhard et al., 2010)). This implies that specific colour cannot be displayed on one medium, and need to be represented with

other colours in a way that looks natural and as close as possible to the original.

In general, there are two main approaches to tone mapping: global tone mapping and local tone mapping. Global tone mapping operators are applied to each value in an image equally, for example, by applying a logarithmic transformation to each colour in the image to reduce the range of colours required. Local tone mapping operators take into account the surround for each point in the image. To preserve the overall impression of a scene and create a realistic rendition of wide gamut HDR data many advanced tone mapping techniques use knowledge of visual perception to influence how colours are perceived, for example, by using simultaneous contrast to make colours appear brighter through an adapted surround (Chiu et al., 1993; Jobson et al., 1996).

2.6 Statistics

The quantitative outcomes of this thesis are analysed with repeated measure linear models, pairwise comparisons of samples and confidence intervals.

In general, the presented experiments consist of several *factors*, which represent experimental changes that are controlled by the experimenter, for example, which colour is presented. A factor has several *levels*, that is, multiple ways the factor is presented or modified. For the example of colours, this could mean three levels: green, blue and red. An experiment can have multiple factors that are crossed. That means all combinations of factors are presented. If we had another factors display with the levels CRT and LED, we would have a 3×2 factorial design, with overall six conditions. To determine how each factor or level influence the outcome of an experiment statistical methods are employed.

During the time the research of this thesis was conducted a paradigm shift regarding statistical approaches began. This is reflected in changing methods used to evaluate the experimental data. While the experiments in Part II are analysed using statistics based on null-hypothesis testing and p-values, the later experiments in Part III are analysed using “new” statistics, which focuses on interpreting effect size measures and comparison of

confidence intervals.

The following descriptions should serve as a short overview of the statistical methodology and a guide on how to interpret the presented results. For a more detailed explanations and mathematical background more specialised literature on quantitative analysis is available, for example Field (2013), Henson (2006) or Cumming (2013).

2.6.1 Omnibus tests

Omnibus tests analyse the variance in a data set to detect whether a change in an experimental condition is accompanied by a change in the experimental measurements. In this thesis, ANOVA F-tests with repeated measures are used to test for changes in experimental conditions. This means that for each condition each participant provides a data point. The overall data is then analysed for changes between the conditions based on the individual changes between conditions. The outcome indicates whether there could be a change between conditions, but not which conditions differ. Thus, if more than two levels exist for an experimental manipulation, additional analysis of the data is required, for example, follow-up statistical tests or direct visual observation of the data.

The overview of the results of a repeated measures ANOVA will be given in a table, listing the main effects and interactions in each line. They contain the following parameters:

Degrees of freedom. *df* is related to the number of groups that are used in a given test. Both of these values describe the data that was used to calculate the statistics, but not the outcome. For a test involving a single factor the first degree of freedom are calculated as

$$df = \text{number of groups} - 1$$

For a test involving multiple factors they are computed as the product of all the degrees of freedom for all factors. The second degrees of freedom \tilde{df} is related to the number of samples that are used in a given tests. It is

calculated as

$$\begin{aligned}\tilde{\text{df}} &= \text{number of observations} - 1 \\ &\quad + \text{number of participants} - 1 \\ &\quad + \text{number of levels} - 1\end{aligned}$$

F-test statistic (F). The F-value describes the ratio between variance in the data set and the variance that can be explained by the variation of the tested experimental factor. Thus, a high F-value indicates a high degree of influence of the experimental factor on observed outcome, while a low F-value indicates a small effect on the outcome.

P-value (p). This value describes the probability that the observed results would have occurred at random, assuming that the experimental changes had no effect on the outcome. A common threshold to call a result statistical significant is a p-value of 0.05. This practice, however, is under recent scrutiny and in general other ways of determining importance (for example, effect size measures) are advised.

Partial eta squared (η_p^2). This value represents a normalised measure of effect size measure. It is based on the differences between means in the given test and normalised by the observed variance. Thus it has no meaning regarding the original measurement, but can be used to compare the strength of an effect between different measures, factors and experiments. A higher value indicates a stronger effect of the manipulation on the outcome.

2.6.2 Additional Effect Size Measures

As follow-up tests for the omnibus test the differences between conditions are reported as mean paired differences M_D in measurement units and as standardised mean changes d_{diff} (M_D divided by the standard deviation). M_D is useful as it gives an impression of change between two variables in colour units, while the standardised values are useful to make the effect sizes comparable regardless of the measure and experiment.

2.6.3 Confidence intervals

95% confidence intervals (CI) are generated through the Bias-Corrected Accelerated Non-Parametric bootstrapping algorithm⁸. They allow us to interpret the results and their reliability without depending on p-values and significance testing, which are strongly argued against in the current statistical and psychological literature (see Cumming 2013 and Henson 2006 for more details).

⁸<https://github.com/cgevans/scikits-bootstrap>

RELATED WORK

The research presented in this thesis is situated in the area of gaze-contingent displays. This chapter describes previous classifications of GCDs and highlighting the current state of the art. It then proceeds to situate this thesis by surveying the existing literature and creating a classification that highlights GCD techniques that have received less attention. To do this, it describes GCDs according to their intent: improving rendering performance, investigating properties of perception and supporting perception.

3.1 Scope

Eye tracking is a flexible input modality that can be used in various ways. GCDs use the eye tracking data in real time, as opposed to analytical uses of eye tracking where gaze data is collected and analysed at a later point in time (e.g., for psychophysical experiments or user studies). GCDs also use the eye tracking information to change their content in response to the user's gaze movement, without explicit interaction from the user. This is in contrast with deliberate interaction, where the user has to use his gaze deliberately, for example, to activate buttons or select objects.

Previous work under the term “gaze-contingent display” has mostly focused on approaches that follow this schema: (1) find out which content cannot be perceived and (2) find ways to reduce the rendering effort to create an image that looks good to the observer. However, the basic premise of GCDs does allow other approaches too. By considering

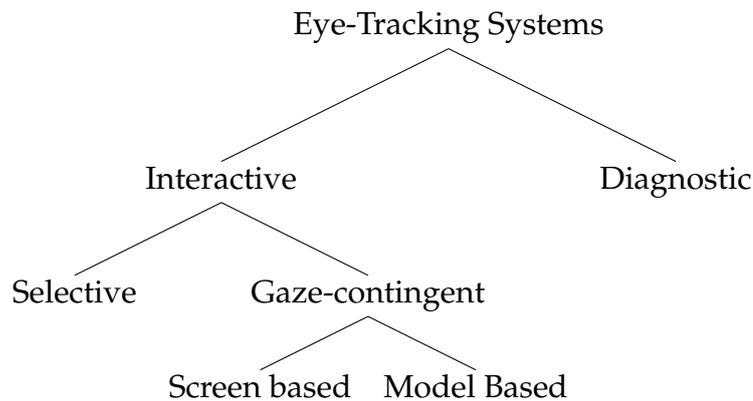


Figure 3.1: Categorisation of gaze-contingent systems proposed by Duchowski (2002)

what is rendered in which part of the retina we can create very specific simulations that can be used to create new kinds of percepts, for example, manipulating specific colour responses by deliberately changing stimulation of rods in specific areas of the retina, thus creating novel impressions for the observer that do not occur during natural viewing.

This overview will focus on systems that fulfil these two criteria (1) real-time use of eye tracking and (2) no interaction that is intentionally initiated by the user. This is a slightly broader definition than previously used and will thus include some techniques that have not previously been considered GCDs.

3.2 Previous classifications

A high-level view of how GCDs are situated in the area of eye tracking based systems was proposed by Duchowski (2002); Duchowski et al. (2004). Their classification (illustrated in Figure 3.1) distinguishes between eye tracking used for offline analysis (that is, “diagnostic”, for example, in research on reading) and systems that use the data in real time for interaction. The later includes both GCDs as well as gaze-interaction, for example, eye pointing. In this categorisations GCDs are defined as systems that degrade content away from the current point of regard and divided up into two categories based on the underlying mechanisms: model-based approaches which change the underlying data (for example, simplifying 3D models) or screen based approaches (for example, varying

	Selective Rendering							
	Screen Based	Model Based	Gaze Interaction	Attention Guiding	Adaptive UI	Diagnostic	Visual Augmentation	Dynamic Stereoscopy
Duchowski (2002)	X	X	X		X	X		
Parkhurst and Niebur (2002)	X						X	
Reingold et al. (2003)	X							
Baudisch et al. (2003)	X	X		X				
Duchowski et al. (2004)	X	X	X					
O'Sullivan et al. (2004)	X	X		X				
Toet (2006)	X	X	X	X	X			X
Farhadi-Niaki (2010)	X	X	X					

Table 3.1: Overview of the concepts that are used to classify GCDs in other surveys.

3. RELATED WORK

rendering resolution across the field of view). Further, they develop this initial categorization and includes attentive user interfaces that use eye tracking as a general means to infer information about the mental state of the user.

Other categorizations have not deviated much from this initial categorization, and have largely kept to these initial categories. Table 3.1) shows an overview of related surveys and the categorisations they use to classify GCDs. There is a strong focus on gaze-contingent multi-resolution displays (GCMRDs), which are exclusively mentioned in Reingold et al. (2003). Parkhurst and Niebur (2002) also focuses heavily on GCMRDs, but also mentions applications that fall into the category of *category visual augmentations*, that aim to change the display in a way to help observer with visual field defects to better perceive the content. While Baudisch et al. (2003) and discuss GCDs as a means to infer the observer's attention. The presented use cases cover matching of rendering to the human visual with the aim of reducing computational load, but also guiding the observer's attention to interesting regions of the display, adding the category of *attention guiding* GCDs (called "easily perceived" displays in the original paper). The same categorization is later on used by O'Sullivan et al. (2004) but discussed from a background of computer graphics with a focus more on the aspect of visual perception, than visual attention. Without introducing a new categorisation Farhadi-Niaki (2010) discuss chromatic degradation of peripheral information, which allows matching of colour information to the varying density of cones in the retina.

The survey of Toet (2006), in contrast to the previous ones, focuses aspects that allow to support the observer through gaze-contingent manipulation of visual perception, for example, to "reducing the attentional visual load", or "enhancing their attentive capacity", thus shifting the focus from reducing rendering effort more to supporting the observer. It is this kind of methodology and view that this thesis will further focus on.

3.3 A new way to look at GCDs

The remainder of this chapter presents a survey of the existing literature on gaze-contingent displays. Similar to Toets' approach, it will highlight the uses of GCDs that aim to support the user in their perception and cognition. It will, therefore, categorise GCDs not solely on the techniques they are applying but their *aim*. Looking at the intent instead of the technology allows a categorisation that reveals not just what is technically possible, but also where the application areas and strengths of GCDs lie, and where the most value can be garnered from them for the people that will use them. In general, there are three major categories that will be highlighted:

Reduce computational cost — This category contains most of the work on multi-resolution displays. The aim of these systems is the improvement of rendering performance, generally by reducing content or content quality in an imperceptible way.

Investigate perception — By changing perceptual properties of a display it is possible to create situations that reveal properties of the visual system. These techniques give insight into how the perceptual system and cognitive processes work. Simple examples are displays that simulate a deformed field of view in psychophysical experiments.

Facilitate perception and cognition — These GCDs try to manipulate the perception of the observer with the aim to help them. This can mean that they make it easier to perceive or understand the displayed content, or add another layer of information that supports a task.

The first two categories have received the most attention (see Table 3.1) of existing work related to GCDs. This thesis is situated in the third category and aims to highlight the usefulness of these kinds of approaches. The following sections will describe existing work in each of these categories.

3.4 Improving Rendering Performance

Previous surveys focus on GCDs that reduce rendering requirements by degrading displayed information in a way that is intended to be imperceptible to the observer. A common approach is to reduce the



Figure 3.2: Example of images shown with varying resolution. In the left example the sheep is attended, in the right example the mountain.

image resolution in the periphery where vision is not as accurate.

The following categorisation will follow an earlier one from Duchowski (2002) which distinguishes between screen-based and model-based approaches. Screen based approaches operate on a pixel level, considering the whole rendered image that is displayed on the screen. Model-Based approaches, in contrast, operate on the underlying data that is used to render an image. For example, in 3D applications, this means quite literally the 3D models (but is not limited to those).

3.4.1 Gaze-contingent Multiresolution Displays

Gaze-contingent Multiresolution Displays (GCMRDs) consider raster images as the product of some pixel based computation. The rendered resolution of large, high-resolution images is often much higher than necessary, considering the information the eye is using at each given point in time. The eye's resolution is highest in the fovea and decreasing in the periphery. Adjusting the rendering to match this resolution could reduce required computations without a noticeable difference to the viewer (see Figure 3.2), especially if the costly computations of each pixel are mostly independent. This is, for example, the case for in ray tracing as demonstrated by Levoy and Whitaker (1990). They found that indeed they could save computational power. However, users would detect the peripheral degradation of the rendered images.

Finding how to make GCMRDs undetectable to the user (or at least not influence his performance) has since been one of the main goals. Duchowski and McCormick (1995) related the peripheral degradation to

pre-attentive processing, taking into account findings from perceptual psychology about attention and visual search concluding that peripheral manipulation needs to be modelled more closely on the Human Visual System as to provide enough information for peripheral processing.

Kortum and Geisler (1996) implement and evaluated GCMRD with varying resolution and achieved a bandwidth compression of up to 94%. Due to technical limitations resolution was above perceptual threshold even in the centre of the image (overall a 256×256 pixel gray-scale images was used). Participants noticed the manipulation, but the effect it had (e.g., noticeable reduced contrast in the periphery) dependent on the stimulus material, that is, more complex photographs showed less detection than text, indicating that spatial frequencies of the image need to be taken into account if degradation should be undetected.

Since then additional investigations have provided more specific requirements for working GCMRDs. They require very fast update times after fixation change (5ms) to be indistinguishable from a normal display (Loschky and McConkie, 2000). They also can incorporate peripheral degradation of colour in addition to spatial resolution (Duchowski et al., 2009). To make GCDs available to general computer graphics Jones et al. (2004) provided a portable GCD implementation based on OpenGL.

3.4.2 Model Based Adaptation

While GCMRs look at the rendering as a per pixel effort that can be reduced by rendering fewer pixels, an alternative approach is to consider the underlying data and computations, which are necessarily independent for each pixel. Data that is outside of the focused area might not need to be modelled as accurately as the data that is attended. One example of this approach is simplifying 3D meshes for rendering (Ohshima et al., 1996; Luebke and Erikson, 1997; Murphy and Duchowski, 2001; Parkhurst and Niebur, 2003; Williams et al., 2003), but can also mean using less complex models of physical simulation (O'Sullivan and Dingliana, 2001; O'Sullivan et al., 2002) or any other kind of computational expensive modelling that can be simplified in unattended areas in a way that is imperceptible to the user.

If objects on screen change their appearance (e.g., the coarseness of the underlying 3D mesh is changed) it is important that these changes happen without attracting the observer's attention. Predicting which changes can go unnoticed and how they need to be applied is, therefore, an important part of determining how to apply model-based simplifications effectively. Reddy (1998); Luebke et al. (2001); Danforth et al. (2000); Watson and Hodges (2004) provide systems and models that aim to predict the visibility of changes based on models of visual perception and attention.

3.5 Simulating Visual Phenomena

Changing the content of the display is also a useful technique to investigate the properties of vision. It can be used to change what is displayed in a way to match different visual properties. This can include limiting the field of view to investigate the limitations of the visual system, or simulating properties of the visual system to make what is displayed more natural. However, what all the techniques in these categories have in common, is that they aim to investigate the actual properties of natural vision.

3.5.1 Diagnostic and Perceptual Research

Since GCDs can directly influence what the viewer is seeing, they are very well suited to investigate human visual perception. The information gained through this research reveals general properties of the human visual system, for example, the varying resolution of the retina or sensitivity to spatial frequencies in specific retinal areas. It is, therefore, no surprise that GCMRDs, and GCDs in general, have been used to gather knowledge about the human visual system. For example Geisler et al. (2006) used a GCMRD to investigate visual search performance on search time, search accuracy, and the resolution fall-off of the display from the point of fixation.



Figure 3.3: Example of lines of text presented using moving windows and peripheral masking, as presented in Rayner et al. (2009). The cross indicates the current gaze position for each line.

3.5.1.1 Moving Window Paradigm in Reading

The moving window paradigm is based on a GCD that controls the amount of visible information using a mask that determines where information is visible (see Figure 3.3 for example). By modifying the mask, the experimenter can control the information available to the reader and gain insight into which information is used to what extent during the process of reading.

This overview does not aim to give a complete account of all reading research that uses a methodology based on gaze-contingency. For more detail, however, a comprehensive overview can be found in a recent paper (Rayner, 2014) by one of the authors first implementing this paradigm which aims to give an overview of the initial research performed by himself and McConkie (McConkie and Rayner, 1975; Rayner, 1975) as well as the findings of the work that built upon their work.

3.5.1.2 Simulate Visual Field Defects

GCDs have been used to investigate the effects of visual field defects by simulating them in controlled environments. Perry and Geisler (2002) proposed a first algorithm that allowed to present videos with a gaze-contingent modified visual field (i.e., changed resolution based on gaze

location) for perceptual research. Fortenbaugh et al. (2007) have used this kind of technique to determine the effects of a limited field of view in navigation tasks.

Similar approaches to generate modification of visual fields have been used to explore the influence of scotomas on visual search (Cornelissen et al., 2005) or the implications of simultanagnosia (only one object at a time visible) on local and global perception (Dalrymple et al., 2010).

GCDs also play an important role in visual neuroscience where they are used for retinal stabilisation of stimuli, for example, to make sure images are always presented at the same location on the retina (Aguilar and Castet, 2011). This allows stimulation of very specific areas of the retina to generate a controlled signal to the human visual system.

3.6 Supporting the User

So far this chapter has looked at systems that are intended to reduce the computational load or to simulate perceptual phenomena for research purposes. However, this is not the full extent of what GCDs can do. The next step is to use GCDs to improve the perception of the viewer beyond the limitations of the hardware (i.e., display) they are using or even their own perception. To show the opportunities of this area, the following description will be inclusive and at times might go beyond the initial scope and include modalities besides vision or even incorporate some user interaction.

3.6.1 Gaze-contingent Lenses

While closer to the realm of gaze interaction, lenses that follow the user's gaze and distort the screen can make it easier to select targets in gaze-pointing tasks (Stellmach and Dachsel, 2012; Ashmore et al., 2005). Depending on the implementation, this can be seen as a GCD that increases selection accuracy and increases the resolution of the displayed information around the gaze-location. It is this last property that has also been used by Mao and Watanabe (2004) in a gaze-directed focus-plus-context technique for flow visualisation. They evaluated different magnification approaches that maximise perceived display resolution for

the flow information. They focused on techniques that avoid distortions at the lens boundaries that might create misleading impressions of the flow in these areas.

3.6.2 Directing the Observer's Gaze

Knowledge about the user's gaze position and history can also be used to ensure that they attend the parts of a display that they are supposed to see, or even make sure they do it in a specific order (e.g., to simulate the scan path of an expert). This can be achieved by using a technique that directs their gaze using covert perceptual manipulations as proposed by Barth et al. (2006). The technique they present uses local contrast modulation (a flashing dot) in the periphery of the field of view to trigger saccades to the desired target and thus guiding the whole scan path.

Following the initial proposal, the technique has been further developed, and different modifications have been explored (Bailey et al., 2009; McNamara et al., 2008; Qvarfordt et al., 2010) It was also shown to provide benefits in applications that simulated the scan path of experts for novice user on mammograms while looking for anomalies (Bailey et al., 2012), guiding the user through non-linear narrative art (McNamara et al., 2012) or increase on recall of information for certain objects in observed scenes (Sridharan et al., 2012).

Another technique based on a similar principle but not from the same line of research is Gazemarks (Kern et al., 2010). This technique looks at the user's gaze position in a task switching context, for example, in a multi-display environment. Just before a task switch, the last gaze position is recorded, and upon return to the task, the user's gaze is guided to where they left. Thus avoiding a reorientation phase and lowering the cost of attention switching.

3.6.3 Assisitive Visual Field Correction

Previously discussed techniques have been used to simulate limited fields of views to investigate their properties. Building on this, areas of a display can also be made visible again to observers that suffer from limited visual fields. Duchowski and Eaddy (2009) implemented a GC system that



Figure 3.4: Example of an image displayed with varying luminance. Once with additional detail in the sky, once with additional detail in the cathedral. The left image would be displayed while looking the the sky, the right image while looking at the cathedral.

allows compensating for visual defects, i.e., scotomata, by remapping the inaccessible visual information to parts of the retina that can process it. This allows the observer to be aware of all the display content at any time, even if it usually would fall into an area they cannot perceive.

3.6.4 HDR

Not only can GCDs be used to influence the field of view or display resolution, but is also possible to simulate effects related to colour vision. The dynamic range that can be viewed by the human eye, or recorded by modern photographic or video equipment is often much larger than what a display can show. GCDs can be used to simulate properties of the visual system like brightness adaptation, which can help alleviate this problem.

Rahardja et al. (2009) proposed the idea of using GCD to extend the dynamic range of a display using a GCD that would adjust the displayed dynamic range based on the luminance values of the currently attended area and thus be able to show high dynamic range (HDR) images on a low dynamic range (LDR) display (see Figure 3.4 for an example). A system implementing this idea was presented by A*Research (ASTARResearch, 2011) and Cheng and Badano (2010) proposed the use of a similar system for medical images. Yamauchi et al. (2011) extended an existing tone-

mapping operator to act in a gaze-contingent way and performed an evaluation of their system, finding that some assumptions of the static method (i.e., size of the area taken into account for applying the operator) do not translate well into a GC system. Mantiuk and Markowski (2013); Rahardja et al. (2009) proposed similar gaze-contingent tone mapping approaches, but so far there is no empirical investigation of the effects of gaze-contingent changes of colour on the perception of colour. Jacobs et al. (2015) simulated loss of acuity, after-effects and other visual phenomena with a GCD and found that brightness perception can be altered.

3.6.5 DOF

As previously described (see Section 2.4) the DOF of the eye provides information about depth and size of objects. It is an inherent property of the eye and its effects are present in everyday viewing, but not usually in computer generated images. A GCD, however, can simulate the natural DOF of the eye in virtual scenes. For early VR applications Rokita (1996) already proposed this idea to increase realism and immersion; even before eye tracking technology became widely available.

However, simulating DOF can also be a benefit in its own right. Hillaire et al. (2008) investigated GC DOF in a monitor-based virtual environment. They found that participants felt more immersed and reported to have more fun during their experience. Also, they reported anecdotal evidence from participants about increased perception of depth. Similar results were found by Mantiuk et al. (2011) and Mauderer et al. (2014), who also used a similar approach and also reported general subjective increases of immersion and perceived depth with GCDOF.

In addition to screen based systems Otani et al. (2008) conducted a study on the influence of GC DOF with a head mounted AR system. They focused specifically on participant's qualitative perception of depth. They evaluated real-time rendered gaze-contingent DOF with a self-defined questionnaire and found that using the GC DOF led to an increase in perceived depth but also a decreased sense of realism.

Not only might GC DOF provide additional information, but it could also serve to alleviate problems commonly associated with 3D displays.

Since they provide binocular information, but do not allow the eye to focus at the depth of the virtual objects this causes what is called a vergence–accommodation conflict. This can lead viewers to experience sickness and headaches Lambooj et al. (2009). To investigate whether GC DOF can help with these problems Leroy et al. (2012) combined stereoscopic displays relying on binocular disparity with GC blur and did indeed find evidence that participants experienced reduced eye strain. However, Vinnikov and Allison (2014) examined gaze-contingent depth of field when used in stereoscopic and non-stereoscopic 3D displays and found that participants did not report better viewing experience with DOF, or even a worse experience. They theorise that the way the DOF is presented plays a large role in its effects. This seems likely considering the overall mixed evidence on the effects.

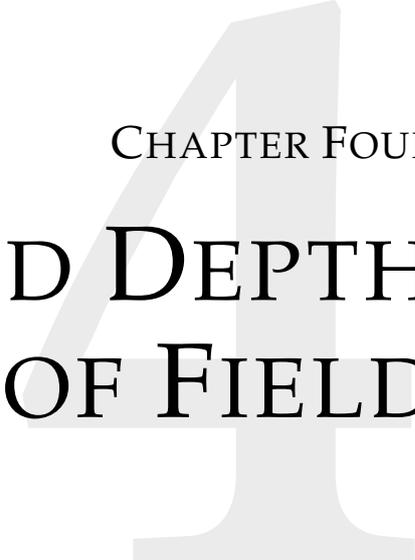
3.7 Summary — State of the Art for GCDs

Applications of GCDs are diverse, and novel ideas are emerging. However, past research has focused on either using GCDs to explore the perceptual properties of the visual system or exploiting these properties with the aim of reducing rendering effort and increasing performance by leaving out visual details that can not be perceived. Some GCD research, however, has started look at the capabilities of eye tracking to support the user and their perception and cognition. This thesis further shows that GCDs can support visual perception and can create benefits from applying perceptual models to optimise the presentation of content for the benefit of the observer. It shows that by manipulating basic properties of the display, like texture or colour, the observer can receive support in higher level task that are related to these features.

III

PART II

AUGMENTING DEPTH PERCEPTION



CHAPTER FOUR

SIMULATED DEPTH OF FIELD

This chapter explores how manipulating texture, in the form of depth of field blur, can change the quality of depth that a display can convey. Blur in images can create the sensation of depth because it emulates an optical property of the eye; namely, the limited Depth of field (DOF) created by the eye's lens system. When the human eye looks at an object, this object appears sharp on the retina, but objects at different distances appear blurred. Eye tracking enables us to reproduce this kind of dynamic depth of field in regular displays, providing an alternative way of conveying depth. This chapter presents *gaze-contingent depth of field* (GC DOF) as a method to produce realistic 3D images, and analyse how effectively people can use it to perceive depth. This chapter is based on parts of the paper Mauderer et al. (2014), which was created in collaboration with Dhanraj Vishwanath, Simone Conte and Miguel Nacenta.

Representing 3D information in flat displays can be valuable to improve the realism of scenes and to increase the amount of visual information that is conveyed to viewers (depth can be considered an additional visual variable). One common technique for providing depth in flat displays is through binocular disparity: different images are presented to each eye, and the visual systems derive depth information from the differences Cutting and Vishton (1995). Although binocular disparity is commonly used in current 3D technologies, it has significant problems: a substantial percentage of people (up to 14% in some investigations Richards (1970))

have difficulty using it, and it can lead to increased visual fatigue, especially when conflicting with other depth cues (e.g., vergence or accommodation), which is commonly the case with flat displays Lambooj et al. (2009).

Fortunately, other depth cues exist that can also be used to convey depth. One such depth cue that is also thought to influence the perception of depth is defocus blur from depth of field (DOF). This is due to the constrained depth of field of the human eye; objects appear more or less blurred depending on their position, and the position of the focal plane Potmesil and Chakravarty (1981); Kolb et al. (1995). Blur patterns can affect the perceived distance between objects Mather (1997) and convey information about the distance of the focused object from the observer Vishwanath and Blaser (2010).

A gaze-contingent display can recreate the blur pattern generated by the eye: objects in the same plane as the object being looked at can be rendered sharply, while objects at different distances will be blurred to varying degrees. This approach has been suggested for virtual reality to increase realism Rokita (1996); Mantiuk et al. (2011); Hillaire et al. (2008); however, it is not clear whether GC DOF can affect the perception of depth. Existing evidence is not in complete agreement (Otani et al. (2008) vs. Sun and Holliman (2009)), and to our knowledge, nobody has conducted an experiment quantifying the degree to which GC DOF can convey depth information. Thus, as a first step to explore the utility of gaze-contingent systems, this chapter will investigate, how well this already existing effect works for estimating depth and relative distances of an object.

4.1 Rendering Gaze-contingent Depth of Field

To create gaze-contingent depth of field, the rendering process uses two main elements: a sequence of images with a range of focal points, and an algorithm to present the images depending on gaze location and timing. This section describes how the different elements come together to simulate DOF. The following assumes the use of a flat display and an eye tracker that can provide the location of gaze within the coordinate space of the display with appropriate accuracy and timeliness. Details of

the hardware that we used can be found in the apparatus sections of the experimental descriptions.

To achieve GC DOF, the display presents an image that is sharp at the viewer's gaze location and appropriately blurred in other regions. A different image is presented for each of the distances of the objects within the scene. These images can be rendered in advance, generated on the fly from a 3D model (as in Mantiuk et al. 2011), or obtained photographically from a real scene, for example, through a sequence of exposures with different lens adjustments (focus bracketing) or through a light-field camera (Georgiev et al., 2013).

This system can use photographic and rendered images, but we use pre-rendered images for our experimental setup since they provide more control over the scene. We do not render the images in real-time to minimise delays in the presentation of the image; generating highly realistic 3D scenes with correct DOF (e.g., using physical based ray-tracing approaches (Cook et al., 1984) as used by software like POVRay and Blender Cycles) in real-time requires significant processing power or specialised hardware. In the following experiment we used Blender Cycles.

The presentation algorithm determines which image has to be presented for a given gaze location. For this, it uses a mapping that provides the index of the correct image for each possible gaze location. This mapping can be derived from the depth map of the scene, which is easy to generate from a synthetic 3D scene as depth information is usually readily available (for example, through the z-buffer). An example of a depth map and derived focus frames is given in Figure 4.1 and a pseudo code example of a lookup sequence from gaze point to frame in Listing 4.1. However, mapping the values from the depth map directly to an image suffers from problems caused by two factors: the inherent delay of focus changes (i.e., accommodation) in the human eye, and the lack of a precise gaze point delivered by the eye tracker.

4. SIMULATED DEPTH OF FIELD

```
1 def gaze_to_frame(gaze_x, gaze_y):
2
3     # lookup in the depthmap that contains the distance for each given
4     # position
5     focus_distance = depthmap[gaze_x, gaze_y]
6
7     # look of the frame that is focused at the given distance
8     frame = depth_to_frame_mapping[focus_distance]
9
10    return frame
```

Listing 4.1: Pseudo code illustrating the mapping from gaze location to frame.

In the human eye, a process called accommodation changes the lens properties to focus. This process is not instantaneous but takes different amounts of time, depending on various internal and external factors, for example, the age of the observer or distance between focus planes (Schaefel et al., 1993; Temme and Morris, 1989). If this process is ignored or the required time is underestimated this can negatively affect the viewing experience (Otani et al., 2008; Mantiuk et al., 2011). While it is beyond this work to create a comprehensive simulation of the human visual accommodation process, our algorithm alleviates this problem by adapting the focus using a transition function, animating the change in focus. Specifically, in the experiment the transition function used was an exponential one: every frame (every 10ms) the distance to the target frame was halved. Listing 4.2 shows a pseudo code example of the algorithm and sequence of frames thus generated can be seen in Figure 4.2. This function is intended to cover large distances quickly, and simulate a more gradual focusing process close to the target plane, all without disrupting the viewing experience. At most a focus change from the back of the box to the front of the box would take $\log_2(100) \approx 7$ frames or 70 ms.

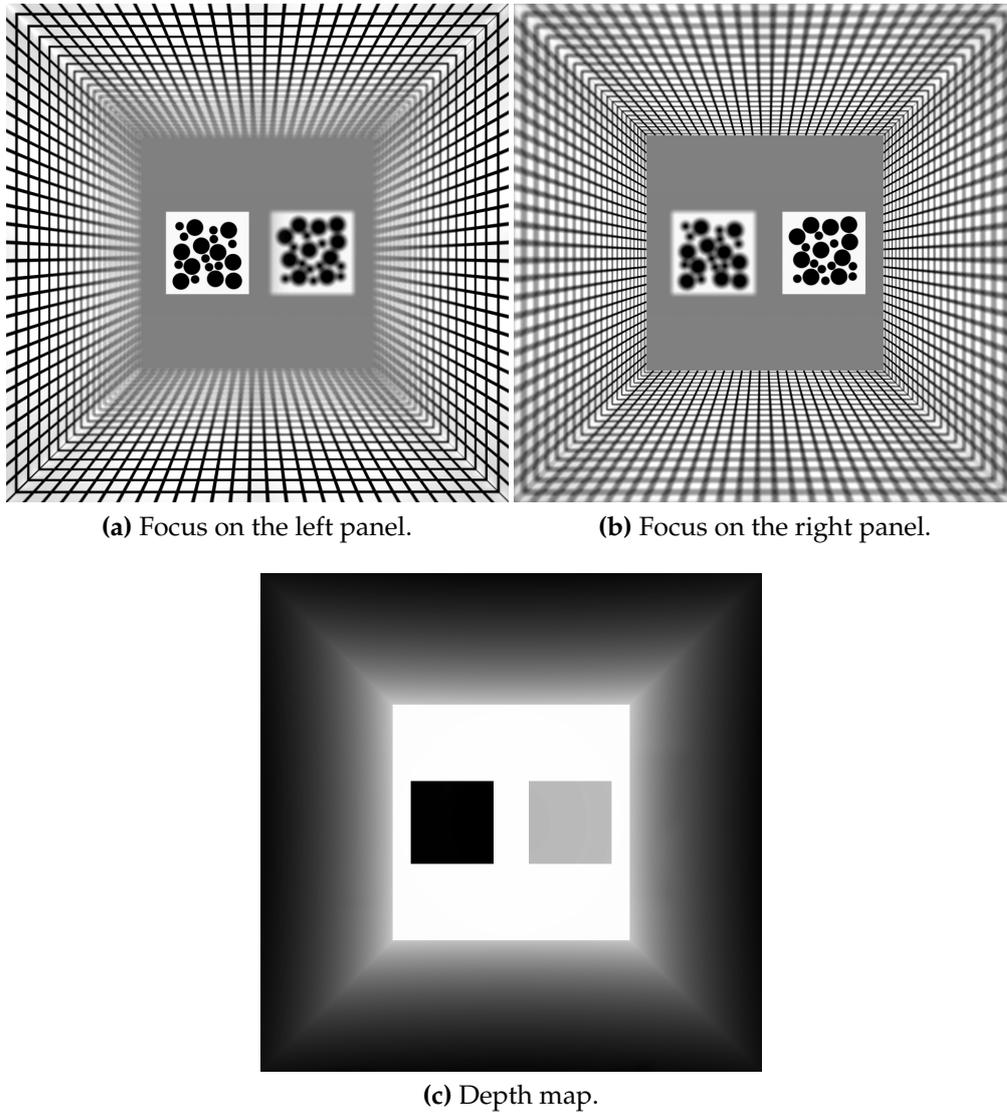


Figure 4.1: Example of the stimuli and the underlying depth map. The left tile is positioned at 10% of the surrounding tunnel depth and the right tile at 90%. Image (a) is presented while the gaze is located on the left patch (or the box at the same depth), (b) while the gaze is located on the right patch (or the box at the corresponding depth).

4. SIMULATED DEPTH OF FIELD

```
1 def gaze_to_frame(current_focus_distance, gaze_x, gaze_y):
2
3     # lookup the target focus distance in the depthmap that contains
4     # the distance for each given position
5     target_focus_distance = depthmap[gaze_x, gaze_y]
6
7     # change the current focus based in the intended target focus
8     focus_difference = target_focus_distance - current_focus_distance
9     focus_change = focus_difference // 2
10    new_current_focus_distance = current_focus_distance + focus_change
11
12    # look of the frame that is focused at the current distance
13    frame = depth_to_frame_mapping[pixel_depth]
14
15    return new_current_focus_distance, frame
```

Listing 4.2: Pseudo code illustrating the mapping from gaze location to frame including an exponential transition function.

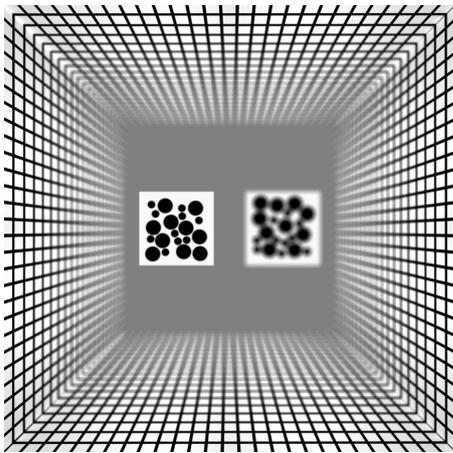
4.2 Experiment

Previous work (e.g., Mauderer et al. (2014); Hillaire et al. (2008)) shows that there is a subjective effect of gaze-contingent DOF for the perception of realistic scenes. However, this does not answer the question of whether GC DOF is an effective and reliable method to convey depth information. In other words, can people extract depth information accurately from GC DOF? This is important for applications where precise information is important (e.g., in information visualisation).

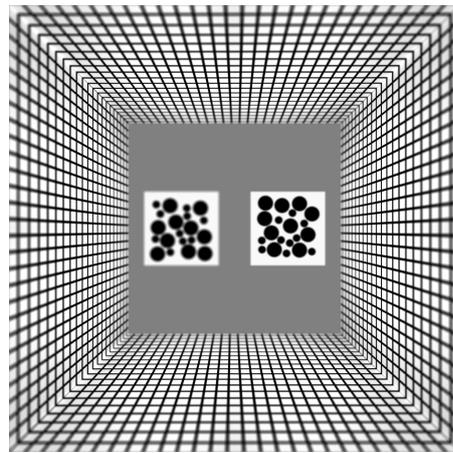
To answer this question we designed a quantitative, controlled experiment that investigates depth perception accuracy through a depth comparison task (i.e., asking participants to estimate the depth of objects). The experiment follows psychophysical methodology from the perception literature and uses abstract objects in a synthetic space to control for possible confounds like size or occlusion.

4.2.1 Apparatus

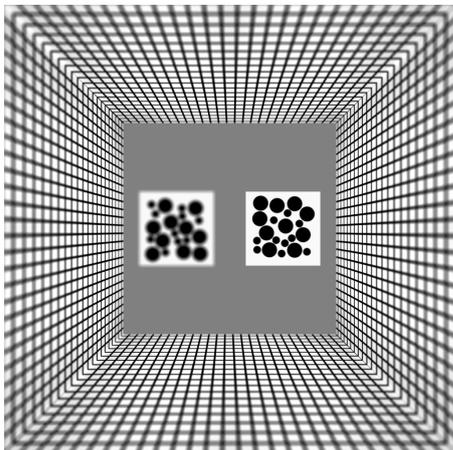
The gaze-contingent display is implemented through an EyeLink 1000 eye tracker that provides data with a rate of up to 2000 Hz with a nominal



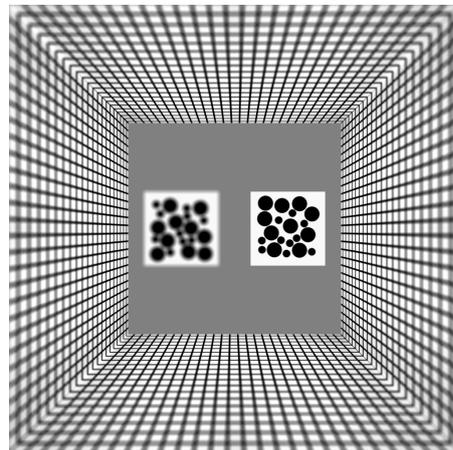
(a) Focus at 0% depth of the box.



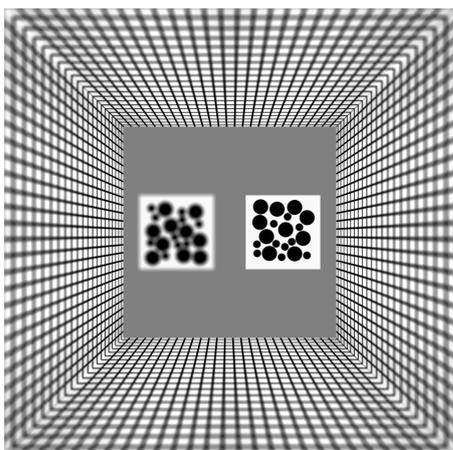
(b) Focus at 50% depth of the box.



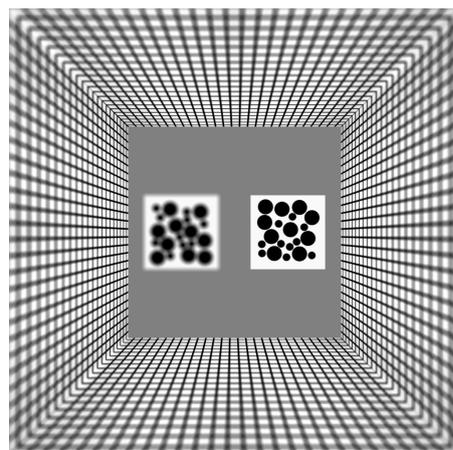
(c) Focus at 75% depth of the box.



(d) Focus at 85% depth of the box.



(e) Focus at 90% depth of the box.



(f) Focus at 95% depth of the box.

Figure 4.2: Example sequence of frames presented during a focus transition from the left patch (located at the front of the box) to the right patch (located at the back of the box). The focus starts on the left patch, and the distance to the right patch is halved (and rounded to the nearest closest frame) each step.

4. SIMULATED DEPTH OF FIELD

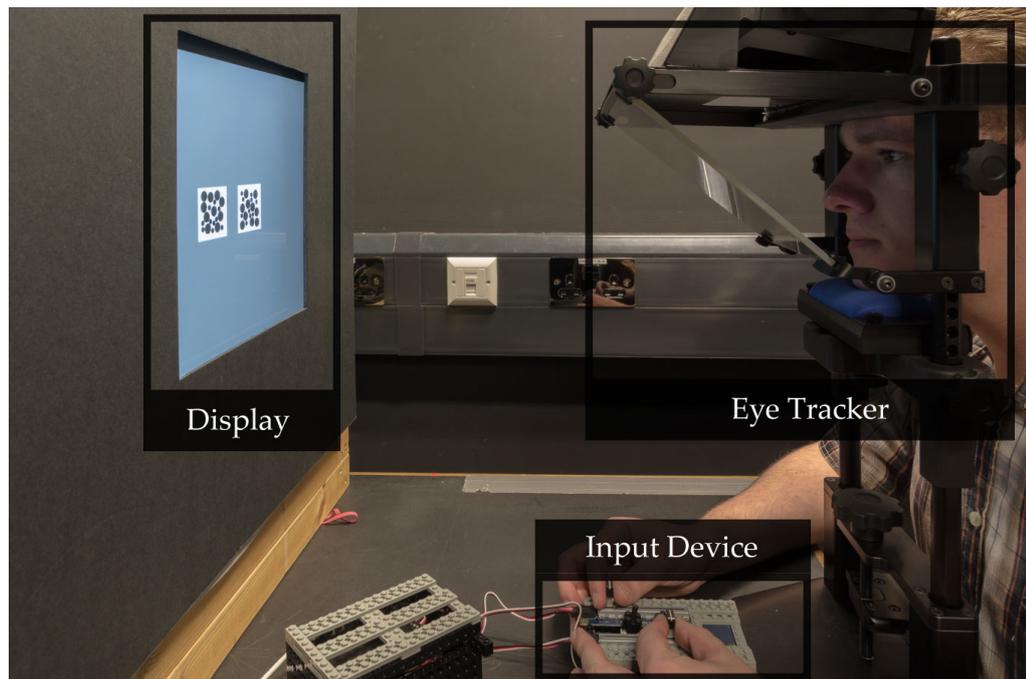


Figure 4.3: Overview of the setup used in the GC DOF experiment.

1.4 ms (SD < 0.4) end to end sample delay¹. The display is a Iiyama HM204DT 22 inch CRT display with a resolution of 1280 px × 1024 px running at 100 Hz. We used a CRT instead of the now more common LCD displays because of their better timing properties (CRTs are still preferred to LCDs and other technologies in perceptual research). To stabilise the participants' head, the eye-tracker was mounted vertically with a tower mount, which provides easier calibration and better quality gaze-tracking. Their face was at a constant 40 cm distance and perpendicular to the screen. See Figure 4.3 for an overview of the setup.

Additionally, We darkened the room for the trials and covered the area surrounding the display with a flat black surface to avoid visual distraction and interference due to the surrounding area of the monitor.

Input responses required recording estimated relative positions of two objects in the visual field through a custom-built Phidget device with two sliders that record positions in a fixed range (0 to 1000), and a capacitive plate that allows participants to indicate the end of a trial. See Figure 4.4 for a detailed view of the device.

¹http://www.sr-research.com/EL_1000.html

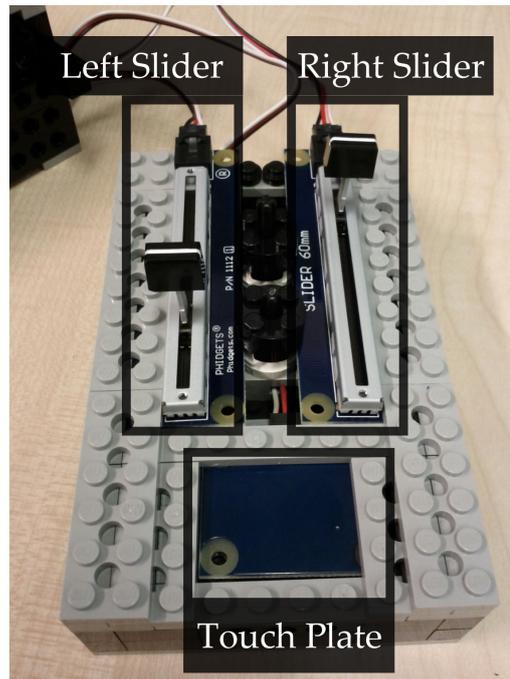


Figure 4.4: Close up of the input device used. It has two sliders that can be moved up and down, as well as a touch sensitive area at the bottom.

4.2.2 Software

We implemented the DOF rendering algorithm outlined in the previous section but with gradual exponential adjustment of blur in accommodation (the distance between currently focused point and target focus point was halved each frame and rounded down). The implementation was programmed in Python 2.7 using PsychoPy 1.75.01² (integrated with OpenGL, allowing for efficient use of graphics card memory); gaze information was retrieved using the Eyelink Python API (Pylink 1.0.0.37).

4.2.3 Task and Stimuli

Participants were presented with two abstract square objects that contain a black-and-white circle pattern that was different between tiles but contained the same number of circles of equal size to make sure that both tiles have equivalent perceived brightness, contrast and information from blur. The objects are perpendicular to the screen plane, aligned with the screen edge, and are floating in mid air. In half the conditions the

²<http://www.psychopy.org/>

plates were surrounded by a patterned square tunnel that started on the display plane and had a virtual depth of 60 cm (see Figure 4.1).

The main task was to estimate the positions of the two objects. Participants used the left and right sliders of the purpose-built Phidget input device to indicate the perceived relative positions of the left and right objects. The end ranges of the sliders represented the front and back ends of the tunnel. We chose relative indirect input for this task because of the possible effect of overlapped motor activity and because seeing their hand could affect perception of distance (see, for example, Witt et al. (2005)).

Each scene had 20 different focal points spaced throughout the area of interest, rendered through Blender v2.64 using the built-in Cycles ray-tracing engine. This was the highest depth resolution that still allowed all the required image data to be ore-loaded into the GPU memory for efficient presentation. The aperture radius of the camera model was set to 0.005 (equivalent to 5 mm), and the field of view was 50°, matching the field of view covered by the monitor. Since depth values in Blender are calculated as distance from the camera position, a correction was applied to produce distances from the image plane instead.

While the tiles were displayed at varying depths, their size was always adjusted to occupy the same visual angle to avoid introducing size as a depth cue confound. The elements in the screen (tunnel and tiles) did not overlap and were rendered separately. To avoid the interference of binocular cues participants wore a one-eye patch on their non-dominant eye.

4.2.4 Procedure and Experimental Design

16 participants (nine female, aged 18 to 33, all had normal or corrected-to-normal vision, nine were right-eye dominant) took part in the experiment. After filling a demographic questionnaire, testing for eye dominance (Miles test) and acuity (Snellen chart) participants put on an eye patch to eliminate binocular depth cues. They then learned the task and performed one block of practice trials and one block for all four experimental conditions.

There were ten practice trials, in which two tiles were shown in the

tunnel, close to the opposite extremes (back and front) and blur was adjusted according to gaze. The other four blocks consisted of variations of two factors with two levels each: gaze-contingency (gaze-contingent GC vs. non-gaze-contingent *NGC*) and background visibility (visible background *VB* vs. no background *NB*) (see Table 4.1 for an overview of the experimental design).

We introduced the gaze-contingency factor as comparison to the baseline. However, the introduction of the background factor corresponds to a less obvious goal. There is a running discussion in the blur perception literature regarding the nature of the type of information provided by defocus blur in natural perception (ordinal vs. quantitative) and whether the context blur of the scene provides valuable information Held et al. (2012); Vishwanath and Blaser (2010). Notice that an appropriately blurred background does contain information about the depth of an object (objects in focus are at the same depth than the parts of the background that is in focus). Including this factor allows us a) a wider generalisation of our results to applications with different backgrounds, b) to draw useful conclusions about the importance of background in GC DOF, and c) contribute to the ongoing discussion on the perceptual mechanisms of blur.

Trials differed in the position of the two stimulus objects (Pos_S). The front tile could appear at 10, 30 and 50% of the box depth (6 cm, 18 cm and 30 cm behind the screen), and the other tile 0, 20 and 40% box depth (0 cm, 12 cm and 24 cm) behind the first one. Each configuration was shown twice, which resulted in 36 trials per condition. In static (non-gaze-contingent) conditions, each of the two trial repetitions for a given position and distance had a different object in focus. The condition presentation order was balanced but the first two conditions were either both gaze-contingent or non-gaze contingent to avoid unnecessary switches and calibration problems (a total of eight possible orders).

Participants had no time limit to complete a trial and indicated the end of each trial by tapping on a large capacitive sensor attached to the near end of the slider input device. Participants were allowed to rest between blocks.

4. SIMULATED DEPTH OF FIELD

	GC (gaze-contingent)	NGC (non gaze-contingent)
VB (visible background)	36 trials	36 trials
NB (no background)	36 trials	36 trials

Table 4.1: Overview of the experimental design. Each cell contains factors for repetition (2), symmetry (2), positions of the front stimulus (3), distance of the back stimulus (3).

4.2.5 Measures

The main raw measurement taken during the experiment was the position of the sliders when participants indicated the end of a trial (at the moment of tap). For practical purposes we report slider positions on a range from 0 to 100 (Pos_I). However, since participants used a variable range of positions in the sliders, and because our measures are relative anyway, we chose to normalise each participant's measurements so that their closest and furthest reported locations over the whole experiment correspond to 0 and 100 respectively.

From the raw position data we derived several additional measures: The difference between the input sliders ($|Diff_I|$), the absolute difference between the input sliders ($I_{|D|}$), and the perceived ordering in depth of the tiles (i.e., whether the left tile was perceived to be in front or behind the right tile). These additional measures are useful to determine whether the perceived depth information in a condition is ordinal (just what is behind what), quantitative (how far an object is from the other), or both (order and estimated distance).

4.3 Results

The experiment has a general repeated measures design with two factors that have two levels each: gaze contingency (G) (gaze contingent GC vs. non-gaze contingent NGC) and the presence of background (B) (background VB vs. no-background NB) (see Table 4.1 for an overview). Importantly, the analyses also use a *position* factor to control for stimulus

#	Factors	df	\tilde{df}	F	p	η_p^2
Absolute Position						
A1	G	1	15	1.26	.280	.08
A2	B	1	15	16.36	.001**	.52
A3	Pos_S	2.05	30.75	8.85	< .001**	.37
A4	$B \times G$	1	15	3.64	.076	.20
A5	$G \times Pos_S$	2.00	29.81	22.83	.702	.02
A6	$B \times Pos_S$	2.36	35.33	5.08	.008**	.25
A7	$B \times G \times Pos_S$	2.68	40.19	0.42	.716	.03
Depth Difference						
B1	G	1	15	3.93	.066	.21
B2	B	1	15	0.94	.349	.06
B3	$Diff_S$	2.51	37.64	1.80	.172	.11
B4	$B \times G$	1	15	5.21	.038*	.26
B5	$G \times Diff_S$	2.25	33.81	2.37	.103	.14
B6	$B \times Diff_S$	4	60	1.91	.121	.11
B7	$B \times G \times Diff_S$	2.30	34.57	0.68	.534	.04
Unordered Depth Difference						
C1	G	1	15	4.73	.046*	.24
C2	B	1	15	5.05	.040*	.25
C3	$ Diff_S $	1.12	16.77	34.83	< .001**	.70
C4	$B \times G$	1	15	0.16	.698	.01
C5	$G \times Diff_S $	1.11	16.67	5.78	.025*	.28
C6	$B \times Diff_S $	2	30	0.21	.810	.01
C7	$B \times G \times Diff_S $	2	30	0.02	.982	.00
Depth Order						
D1	G	1	15	8.57	.010*	.36
D2	B	1	15	0.40	.539	.03
D3	$B \times G$	1	15	0.05	.833	.00
Meta-Analysis of Correlations						
E1	G	1	15	26.26	< .001**	.64
E2	B	1	15	0.71	.412	.05
E2	$G \times B$	1	15	0.56	.465	.04

Table 4.2: Results of the statistical analysis of the experimental measurements. Significant results ($\alpha = .05$) are marked by an asterisk, highly significant results ($\alpha = .01$) by two asterisks.

4. SIMULATED DEPTH OF FIELD

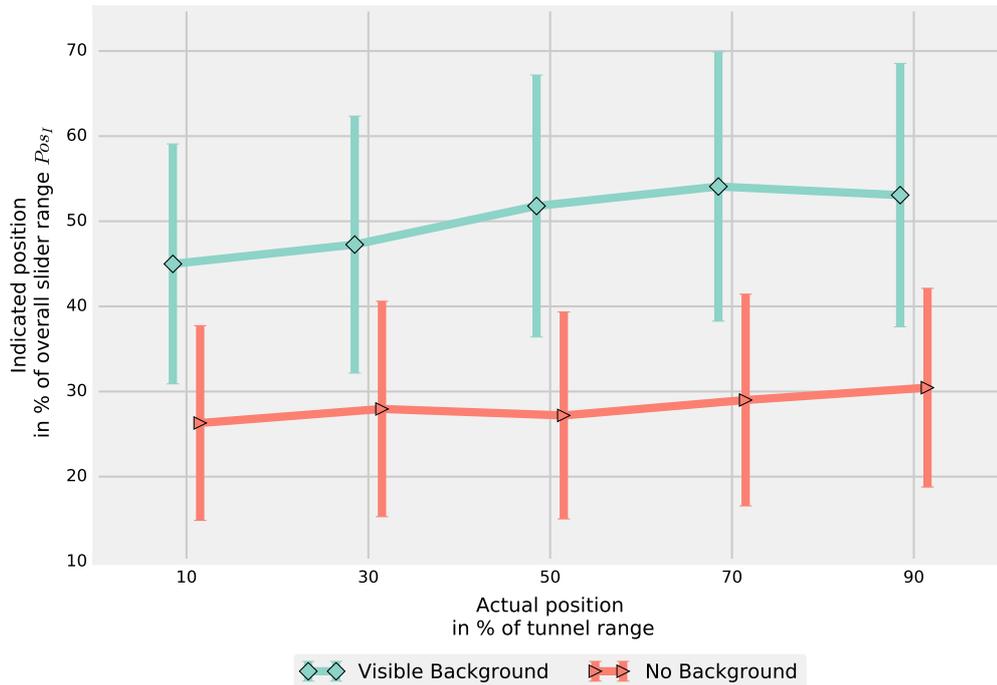


Figure 4.5: Indicated positions Pos_I against actual positions Pos_S in the two background conditions.

object position; this factor is what differentiates the different analyses below and can be one of: a) the absolute position of objects (10, 30, 50, 70 or 90), b) the distance between objects (−40, −20, 0, 20 or 40), c) the absolute distance between objects (0, 20 or 40), or d) the ordering of objects (left in front, right in front). Tests that do not show an effect related to the position factor (e.g., timing) are of little interest to us, since they do not relate to the participant’s ability to use the stimuli information to discriminate different depths and thus we omit discussing them.

Repeated trials in the same cell were averaged before analysis, and when the assumption of sphericity was broken (i.e., a Mauchly’s sphericity test was significant) we applied the Greenhouse-Geisser correction. Error bars in plots represent 95% confidence intervals unless otherwise stated.

4.3.1 Absolute Position

The first test is designed to estimate whether participants estimated positions differently depending on the virtual positions of the stimuli; in other words, whether participants were able to extract information

from the stimuli to judge the absolute positions of the tiles. For this, we performed a $2 \times 2 \times 5$ repeated-measures ANOVA of the individual position responses for the tiles. We expected to see strong main effects of the stimuli positions on the perceived positions of objects, if not in all cases, at least for certain conditions.

We did observe a significant main effect for Pos_S (Table 4.2: A3) and the background condition (Table 4.2: A2) as well as an interaction between them (Table 4.2: A6). Contrasts reveal a linear relationship for Pos_S ($F(1, 15) = 16.77, p = < 0.001, \eta_p^2 = .53$). However, we did not find an effect involving G (Table 4.2: A1) or G and Pos_S (Table 4.2: A5, A7).

These results suggest that some absolute information is extracted from blur overall: Stimuli representing objects that are further away cause further judgements, with a slight improvement when there is background. However, there are no significant effects of gaze contingency, and a quick look at Figure 4.5 shows that the linear relationship is not very pronounced and is indeed small compared to the amount of noise (evident from the large 95% confidence intervals) for both background and non-background conditions.

4.3.2 Depth Difference

The absolute measurements could have been affected by the indirectness of the input device, and since many perceptual effects are relative, we also tested the difference in the judgements of the left and right object as compared to the difference in position of the tiles. This analysis is analogous to that of the previous section, but the position is instead encoded as relative differences in object position in both the dependent variable and the $Diff_S$ factor.

Surprisingly, none of the tests involving $Diff_S$ (Table 4.2: B3, B5, B6, B7) were significant. This indicates that participants were even worse at comparing the distance between objects.

4.3.3 Unordered Depth Difference

A possible explanation for the previous result is that blur might be good for judging the magnitude of depth differences between objects, but not

4. SIMULATED DEPTH OF FIELD

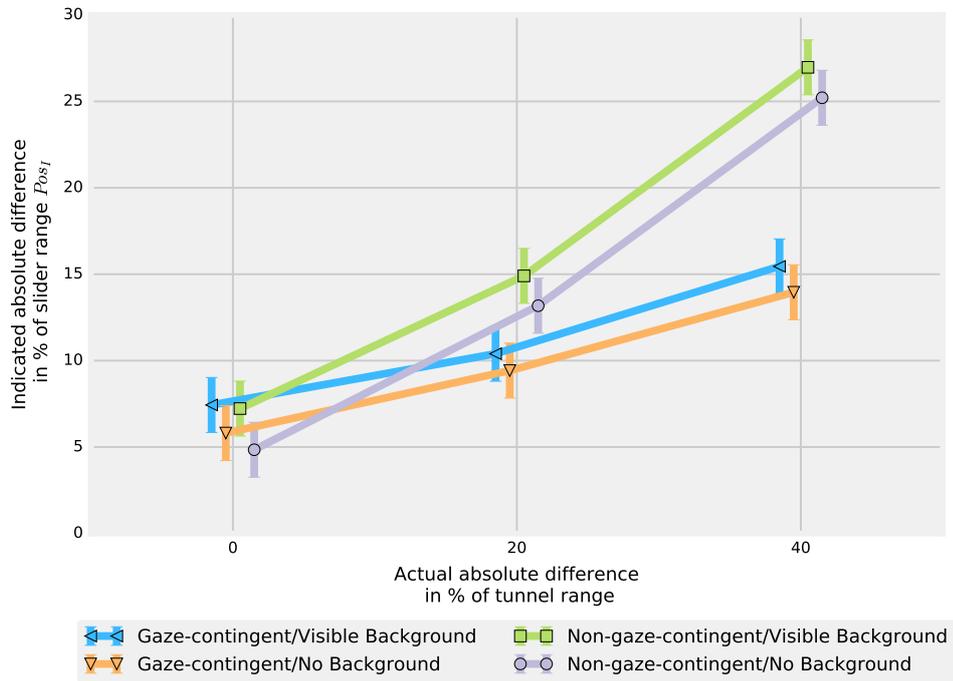


Figure 4.6: Absolute stimulus difference $|Diff_s|$ against the absolute indicated input difference $I_{|D|}$.

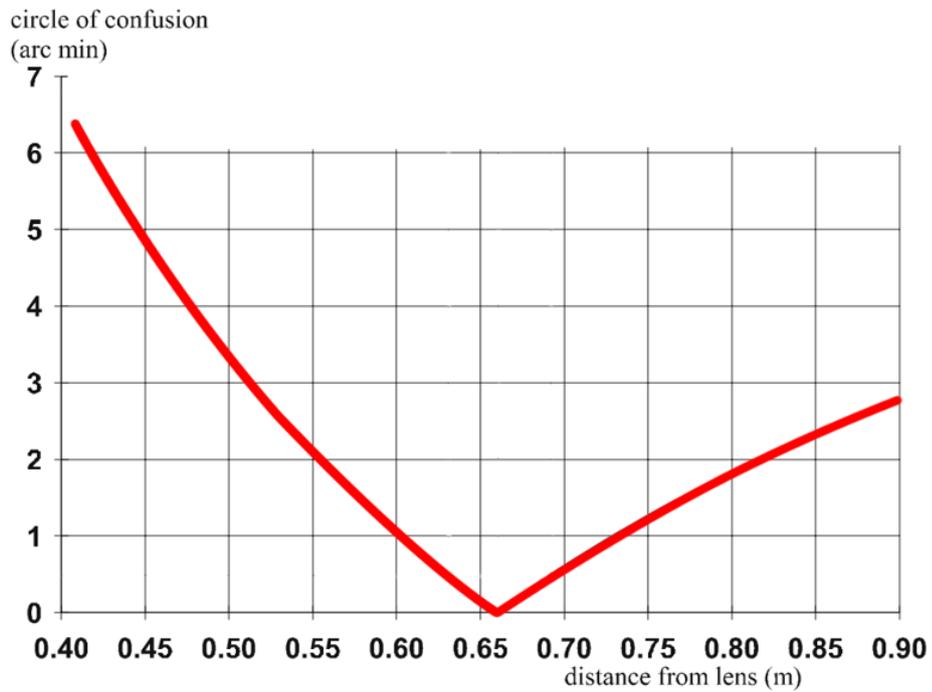


Figure 4.7: Blur strength (size of circle of confusion) relative to distance of focal plane. Based on Brooker and Sharkey (2001).

to estimate the direction of this difference. There is theoretical backing for this theory, as blur is created symmetrically around the focal plane, which means there are equivalent levels of blur both behind and in front of the focal plane (see Figure 4.7). To test for this we used the unordered depth distances in the stimuli ($|Diff_S|$ - 0, 20 and 40) with a similar transformation in the dependent variable: $I_{|D|}$.

The results (see Figure 4.6) indicate that this is indeed the case: all main effects were significant (Table 4.2: C1, C2, C3), as well as the interaction between $|Diff_S|$ and G (Table 4.2: C5). A look at Figure 4.6 and the interaction reveals that gaze-contingent conditions resulted in a smaller range of responses: static representations of blur result thus in a stronger impression of depth.

4.3.4 Depth Order

Since the previous test eliminates the ordinal information, it makes sense to run its counterpart to test whether participants could extract pure order information (i.e., determine which object is in front). We first converted the positions of objects to a binary location factor (left tile in front vs. right tile in front) as well as the participant responses (left slider in front vs. right slider in front) and determined the agreement between them. For this analysis, we excluded trials for which $Diff_S = 0$, as these do not allow a correct ordering decision.

Results indicate a significant main effect for G (Table 4.2: D1) with GC ($N = 32$, $M = 0.55$, $SD = .02$), showing a higher rate of correct ordering than NGC ($N = 32$, $M = 0.48$, $SD = .01$). It is important to notice, however, that the correctness rate for GC is not much above chance.

4.3.5 Individual Differences

It is also possible that beyond the overall effect of the different conditions, individual differences between observers might explain partly the fragmented results; in other words, could certain participants extract information very effectively while others could not?

To test this, we evaluated the accuracy of individual participants at depth ordering. The results are displayed in Figure 4.8, and the results paint an

4. SIMULATED DEPTH OF FIELD

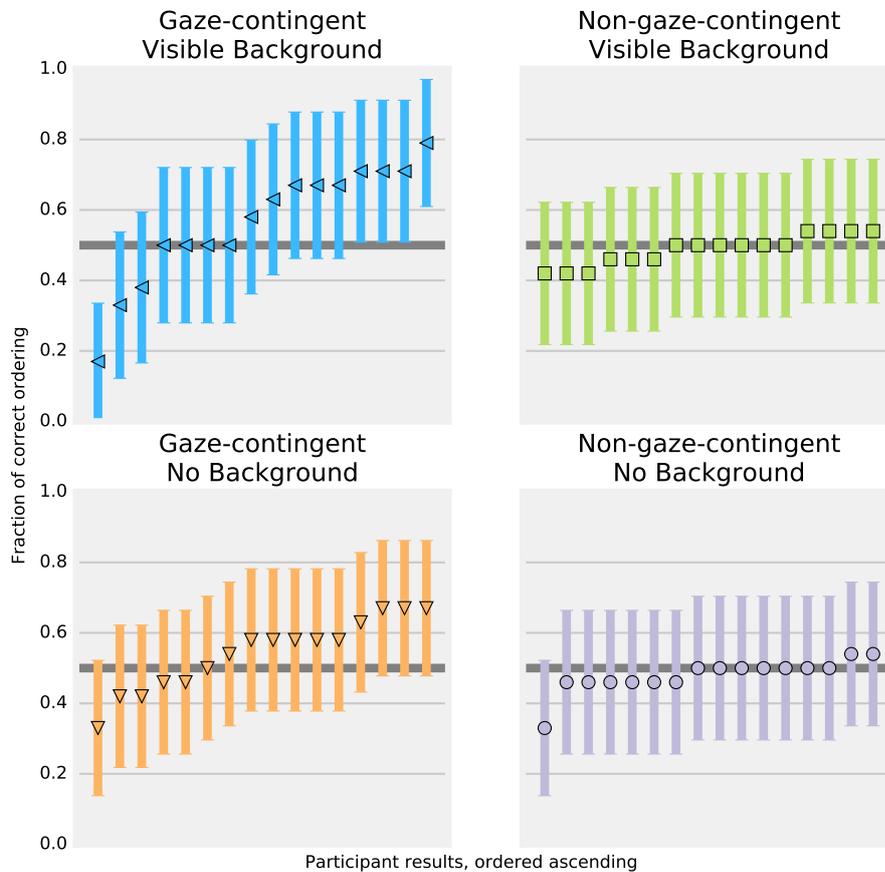


Figure 4.8: Individual performances for depth order discrimination.

interesting picture: individual differences are highly visible in the gaze-contingent with background condition, with four participants scoring significantly above chance, and one significantly below chance (average correctness is above chance when the 95% interval of confidence does not touch the 50% line). These results show that the ability to perceive depth ordering with GC DOF is not universal, and at least one person interpreted the information in a consistently erroneous way.

4.3.6 Meta-Analysis of Correlations between Estimated Depth and Displayed Depth

As a complementary posthoc analysis to the initial investigation of estimated depth difference, we analysed the correlations between estimated depth difference and displayed depth difference in the different

conditions. we conducted a 2×2 ($G \times B$) RM-ANOVA over each participants' coefficient of determination R^2 between $|Diff_I|$ and $Diff_S$ in each of the conditions. we chose R^2 over r as we are more concerned about consistency and explanatory power than the sign of the relationship. The results show a significant main effect for G (Table 4.2: E1) indicating that there was a stronger correlation in the gaze-contingent condition ($N = 32$, $M = .082$, $SD = .01$) than in the non gaze-contingent condition ($N = 32$, $M = .012$, $SD = .01$).

4.4 Discussion

This experiment contributes results that extend our knowledge about the usefulness of gaze-contingent DOF and blur to represent 3D information.

4.4.1 Blur and GC DOF Blur's Contribution

Our findings indicate that gaze-contingent blur contributes to depth perception; this is the first quantitative evidence of depth perception from blur with a GC DOF setup. When considering both static and gaze-contingent blur, we found a general contribution of blur to the perception of absolute depth, and to the perception of depth differences between objects if we only consider magnitude. GC DOF also allows better than chance discrimination in the spatial ordering of objects, although static blur seems to have a more pronounced effect in the detection of depth differences between two objects.

The effects, however, are small. When considered across all participants and conditions, the ability of people to judge ordinal depth is significant above chance, but just by 5 percentage points. Similarly, quantitative judgements of depth are also statistically significant, but small if compared with the degree of variability seen in the accuracy of the depth judgements. This indicates it is unlikely that GC DOF alone is enough to convey accurate depth information, but it provides still an improvement and might be able to enhance existing 3D techniques.

4.4.2 How Depth from Blur Works

The results provide insights in how blur provides information about depth. If we consider first only static stimuli, it is not surprising to find that blur does not provide ordering information since it is sign-ambiguous: the more blurred object could be in front of or behind the focused object (Marshall et al., 1996; Held et al., 2012). Static blur is also limited by the fact that it obscures information in the blurred regions. This can be problematic for the perception of the whole scene (Sun and Holliman, 2009). However, the improvement in ordinal depth perception in the gaze-contingent conditions suggests that ordinal depth perception could be informed by the dynamic blur transitions between focal planes.

We also found that the presence of GC DOF yields a better correlation between observed object distances and actual object distances in the presence of contextual information. With background, gaze-contingent depth of field yielded greater absolute magnitudes of perceived depth. These results are consistent with previous findings reported in the perception literature reporting that blur difference between isolated objects is by itself insufficient to convey quantitative depth (Marshall et al., 1996), but they also show that blur can influence the perceived depth in the presence of additional context, for example, the box in experiment's scene.

However, this result needs to be followed up by further experiments as the backgrounds we used all had defocus blur consistent with the viewing parameters. To know whether the advantage is caused by the background blur pattern, or just merely the presence of an additional context, we need to compare an additional condition with the unblurred background.

4.4.3 Individual Differences

Further analysis revealed that depth from blur is not universal; although some participants were particularly good at deriving depth from the GC DOF, others seemed to be unable to extract information from it. It is unclear whether this can be taught or, as in binocular displays, it is inherent to the perceptual processing capability of some people (Richards, 1970).

4.5 Conclusion

This chapter presented an experimental investigation of gaze-contingent depth of field, studying its influence on quantitative depth information. It contributes evidence that GC DOF increases perceived depth and add validity to prior assumptions about the usefulness of simulated DOF by confirming these findings using methodology validated in perception research. It also demonstrates that GC DOF does contain information about depth order and relative spatial position of objects. This information is, however, limited. The findings show that GC DOF has to be used with caution in applications that try to communicate accurate information such as information visualisations.

In the context of the overall thesis, this chapter provides empirical evidenced that GCDs can be used to augment visual perception, that is, improve aspects of depth perception. This kind of augmentation is purely passive and relies on meta-data that is easily accessible in already existing systems, for example, 3D rendering engines or can be captured with common devices (e.g., Android phones that can capture images with depth information³). This makes it a compelling use case for eye tracking in desktop applications, as it is an easy to implement add-on to existing technology.

³<http://lightfield-forum.com/2014/04/lens-blur-google-camera-app-for-android-gets-refocus-and-adjustable-depth-of-field/>

CHAPTER FIVE

SIMULATED CHROMATIC ABERRATION

The last chapter has shown that gaze-contingent simulation of DOF blur can increase depth perception and separate objects in depth, but that the ordering of objects might not always be clear. While GC DOF helps to indicate that two objects are separated in depth, it is not reliable to show which of them is closer to the observer. This could be a problem caused by the sign ambiguity of blur: for a given amount of blur there is always a distance in front as well as behind the focal plane that could produce this blur (see Figure 4.7). So an additional source of information is needed to resolve this ambiguity. This chapter will look at chromatic aberration (CA) as a potential solution to this problem.

The assumption that all light is focused at the same point is a simplification of the actual optical process. In reality, light is refracted by the lens differently according to its wavelength, leading to different amounts of blur for different colours (see Figure 2.5). In photographic images, this can be visible as colour fringes (see Figure 5.1 for an example) and is called axial chromatic aberration (as opposed to transverse chromatic aberration which is caused by misalignment of differently coloured image planes). Chromatic aberration contains information about the relative positions of objects (Garcia et al., 2000; Sanson et al., 2012) and thus might be able to resolve the sign ambiguity of GC DOF.



Figure 5.1: An example of purple fringing. Image .

This chapter presents an extension of the previous GC DOF rendering approach that also includes axial chromatic aberration. DOF itself has already shown to be a beneficial addition to 3D rendering, which increases perceived realism and depth perception. Building on this could show that a more physically faithful implementation could inherit all its benefits while further alleviating its inherent drawbacks of sign-ambiguity.

To show that this approach could be of practical use the rendering is implemented in an existing rendering tool (Blender Cycles), bridging the gap between optical faithfulness and ease of use. This chapter investigates the effect of the CA thus created with an experiment very similar to the one presented in the previous chapter. The results of the experiment were inconclusive about the usefulness of CA. This might be because either there is no benefit of using CA for the human visual system, or due to the limitations of the rendering approach.

5.1 Modelling the Chromatic Aberration of the Human Eye in Blender

A simulation of chromatic aberration should be closely modelled on its physical description. The mathematical models used to describe a lens system can be used to extend existing camera models, especially in ray tracing based system, where DOF is rendered through physical simulation already. How these models can be adapted and matched to the parameters of the human eye, is discussed in the following section.

5.1.1 Assumptions

The eye as thin lens The eye can be abstracted as a single thin lens system. While this neglects to take into account some properties of the eye (for example, varying non-opaque media) it allows us to create an easy to use mathematical model, that can describe all the factors that are required to calculate chromatic aberration.

RGB colour model The simplified approach should be able to use the existing RGB pipelines for rendering, but still model the spectral properties that cause CA as closely as possible. For this abstraction, some assumptions about the physical properties and the handling of the data need to be made. Also, each RGB channel will be used to describes a single frequency of light. The chosen frequencies are based on the properties of the monitor used: each frequency represents the peak wavelength of each channel. The values are given as:

$$\lambda_{red} = 650 \text{ nm} \quad (5.1)$$

$$\lambda_{green} = 510 \text{ nm} \quad (5.2)$$

$$\lambda_{blue} = 475 \text{ nm} \quad (5.3)$$

Focus location The next assumption that is that the eye will always be focused on the green channel. This assumption is based on two factors: green is the channel that contains the most luminance information, which is important for the perception of details. The green channel is also located

in-between the two other ones, allowing chromatic aberration to appear symmetrical around it.

5.1.2 Rendering Chromatic Aberration

Chromatic aberration is not usually re-created in computer generated images (Dirik et al., 2006). However, CA can make images look more naturalistic, and is thus used in more sophisticated rendering engines. There the CA can be generated through ray tracing techniques that simulate or approximate physical lens systems (Lee et al., 2010; Wu et al., 2010; Steinert et al., 2011).

As the literature indicates that CA could add additional depth information and increase realism, it seems plausible to extend the previous work on GC DOF rendering. This could solve problems of ambiguity and strengthen the effects of the GC DOF without CA, allowing better depth judgements and potentially resolving the ordering accuracy.

5.1.3 Colour Abstraction

The following model does not require specific handling of spectral information in the rendering pipeline, allowing it to be used in a common rendering engine like Blender. While there are physically correct rendering engines that can produce correct reproductions of CA for varying media and camera models (e.g., PBRT¹) these are not commonly used to create images outside of specialised use cases. Conventional rendering engines only deal with RGB values and can not easily be extended to work on spectral colour representations, which would be required for correct reproduction.

5.1.4 Modelling the Eyes Chromatic aberration

The eye can be abstracted as a single thin lens system. Using this model the focus planes for the different colour channels can be computed using the thin lens equation (see Equation (2.1)).

To use this equation we need to gather all the required parameters. The image plane is represented by the distance of the retina to the eye's lens,

¹<http://www.pbrt.org/>

5.1. Modelling the Chromatic Aberration of the Human Eye in Blender

and therefore fixed, as is the refractive index of the lens (see below). The curvature r is variable and changes to change the focal plane to the desired distance.

Thus if we know the distance of an object that is focused, we can compute the curvature of the lens based on the assumption that $\lambda = \lambda_{green}$. Given the curvature we can then compute the resulting focal planes for λ_{blue} and λ_{red} .

To represent the eye as a thin lens, we need a summarised refractive index for the lens system that abstracts the different ocular media. Fortunately, this abstraction is available, and the refractive index as a function of wavelength has been derived by Atchison and Smith (2005) (Eq. (8b)) and is given as

$$n_{\lambda} = 1.32008 + 4.75654/(\lambda - 2.18.358) \quad (5.4)$$

5.1.5 Rendering CA in Blender Cycles

Blender² is a open source application for 3D modelling and rendering. It provides ray tracing capabilities through its rendering engine *Cycles*. Blender also provides scripting capabilities that allow flexible to modify and automate parts of the rendering process. The open source nature of Blender means it is freely available and everyone can use it and reproduce the algorithms described herein. While there are rendering engines that provide more physical accuracy (e.g., PBRT³, Blender is an application that is similar to rendering engines that are used to create media like, videos, games or common computer generated images based on RGB colour models.

The camera model that Blender Cycles uses is a standard camera model that is specified by position, orientation, field of view, aperture radius and focus distance.

The final image will be a composite of three images that are rendered separately, one for each RGB channel, with camera parameters determined by the previously presented equations. The main difference between each

²<https://www.blender.org/>

³<http://www.pbrt.org/>

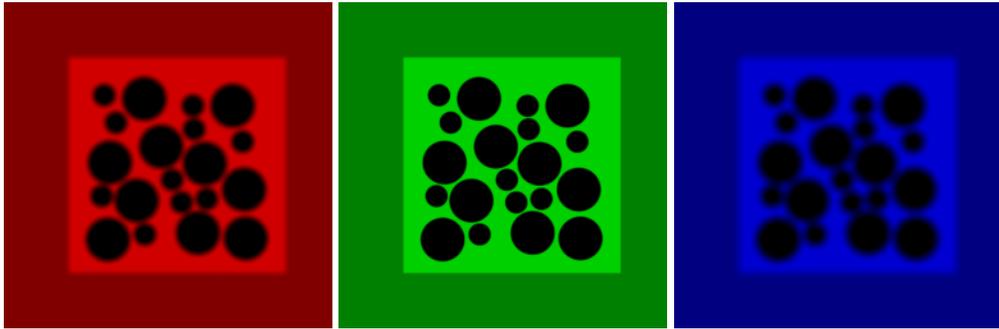


Figure 5.2: An example of the different focus in different colour channels. The middle picture represents the green channel and is in focus. The in the red image the focus is behind the patch. For the blue picture the focus is in front of the patch.

image is (a) the focus plane and (b) the resulting component colour. This means that each image will have blur according to the assumed refractive index λ for the channel colour and then will be composed according to its channel (see Figure 5.2 for an example of the rendered channels).

The green channel is rendered at the actual target focus distance, allowing us to infer the accommodation state of the eye, which can be described by the radius r of the lens. A specific curvature of the eye is required to achieve focus in this distance according to the thin lens model Equation (2.1). Once we know r we can calculate the focus planes for red and blue, and use these to render the other two images. Since blur will differ between the separate image planes, the resulting image will exhibit the colour fringes similar to those caused by CA (see Figure 5.3 for two examples of composite images). Changing the focus will also affect the overall appearance of the image, especially which areas of the display exhibit colour fringes and in which colour they appear. Examples of the varying focus and the varying amounts of CA exhibited in the different conditions can be seen in Figure 5.4.

5.2 Experiment

To investigate the effect of adding CA to the GC DOF system presented in the previous chapter we performed a psychophysical experiment that was very similar to the experiment performed to investigate the effects of the basic GC DOF (see Section 4.2: Experiment). The experiment (task,

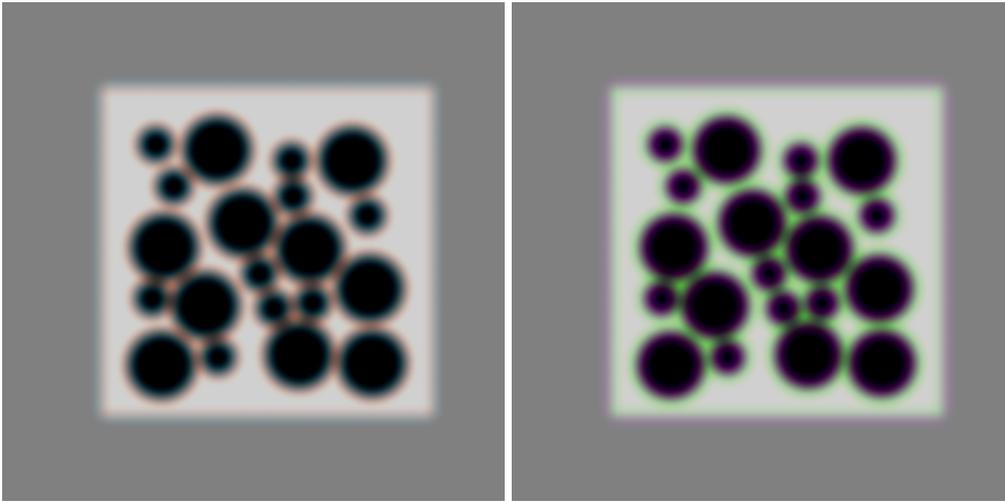


Figure 5.3: An example of CA renderings used in the experiment. The left image represents a patch at position 70, with focus at 10, and a lens opening of 0.07. The right image represents a patch at position 60, with focus at 20, and a lens opening of 0.01.

apparatus) was mostly identical to the setup described in Chapter 4 except for the changes described in the following sections.

5.2.1 Procedure and Experimental Design

24 participants (14 female, aged 17 to 51, $M = 23.63$, $SD = 7.61$, all with normal or corrected-to-normal vision, 14 were right-eye dominant) took part in the experiment. After filling a demographic questionnaire, testing for eye dominance (Miles test), acuity (Snellen chart) and colour vision deficiencies (Ishihara Color Test) participants put on an eye patch to eliminate binocular depth cues. They then learnt the task and performed one block of practice trials and one block for all four experimental conditions.

There were ten practice trials, in which two tiles were shown in the tunnel, close to the opposite extremes (back and front) and blur was adjusted according to the gaze position / distance of attended object. The other four blocks consisted of variations of the chromatic aberration: no CA as a baseline, and three varying levels of CA determined by the position of the image plane with values of 0.01, 0.024 and 0.07. None of the experimental trials showed a background, and objects were always displayed on neutral ground.

Trials differed in the virtual position of the two stimulus objects (Pos_S). The front tile could appear at 10, 30 and 50% of the box depth (6 cm, 18 cm and 30 cm behind the screen), and the other tile 0, 20 and 40% box depth (0 cm, 12 cm and 24 cm) behind the first one. Each configuration was shown twice, which resulted in 36 trials per condition. The condition presentation order was balanced and all 24 combinations were tested.

Participants had no time limit to complete a trial, and indicated the end of each trial by tapping on a large capacitive sensor attached to the rear end of the slider input device (same as in the previous chapter, see Figure 4.4). Participants were allowed to rest between blocks.

5.2.2 Measures

The main raw measurement taken during the experiment was the position of the sliders when participants indicated the end of a trial (at the moment of tap). For practical purposes we report slider positions in a range from 0 to 100 (Pos_I). Because participants frequently used only a limited range of positions the ranges are normalised for each participant's values to the range 0 and 100.

5.2.3 Results

The experiment has a general repeated measures design with one factor that had two levels. The condition without CA served as a baseline.

Repeated trials in the same cell were averaged before analysis, and when the assumption of sphericity was violated (i.e., a Mauchly's sphericity test was significant) we applied the Greenhouse-Geisser correction. Error bars in plots represent 95% confidence intervals unless otherwise stated.

5.2.3.1 Power Analysis

Based on the results of the experiment on GC DOF we performed an a priori power analysis using G*Power (Faul et al., 2007). We used the previous experiment on GC DOF as a baseline and assumed that the effect size in this experiment should be equivalent in size to the previous findings ($\eta_p^2 = 0.36$). Based on this assumption the implied power this experiment for detecting such an effect using a repeated measure ANOVA

5. SIMULATED CHROMATIC ABERRATION

Compared Conditions	Difference between means	<i>df</i>	<i>t</i>	<i>p</i>
$CA_{NA} \times CA_{0.01}$	0.05	23	1.80	.09
$CA_{NA} \times CA_{0.024}$	-0.04	23	-1.60	.24
$CA_{NA} \times CA_{0.07}$	0.00	23	-0.11	1

Table 5.1: Results of the post-hoc analysis between CA conditions and baseline using Bonferroni-Holm corrected t-tests.

is 0.99999, thus giving high confidence in the ability of the experiment to detect an equivalent effect.

5.2.3.2 Depth Difference

We performed an RM ANOVA for the four conditions and found a significant effect for the CA level ($F(3,69) = 2.91, p = .04, \eta_p^2 = .11$) however, none of the posthoc tests between CA and the baseline showed a significant effect (see Table 5.1)

5.3 Discussion

The results indicate that CA as it was implemented and tested, is unlikely to lead to meaningful improvement in the perception of ordering between objects in a GCDOF display. While further study of CA might show that there is some effect on perception, in general, the power analysis indicated that the effect would be smaller than the previously studied effect of GC DOF. Thus the value for practical applications might be rather small, especially considering the computational cost required to generate the CA at this time.

This means that while adding CA to images can be used for aesthetic reasons, it does not convey depth information beyond what is contained in DOF. A very faithful representation, therefore, does not convey additional benefits over easy approximations (e.g., applying arbitrary Gaussian blur instead of depth dependent aperture based blur).

Further research on simulated CA could be interesting nonetheless for insights into the perceptual system. More optical faithful rendering that uses spectral ray-tracing could lead to different CA patterns that closer

correspond to the actual patterns projected onto the retina. To achieve this a new investigation would have to use (a) spectral ray-tracing, taking into account the full light spectrum and computing dispersion accordingly and (b) use a more comprehensive model of the eye that can take into account the actual ocular media of the eye and potential variation of CA across the retina due to its curvature. Also, even smaller effect sizes might be of relevance in this area, even if they might not be of high practical use in real world tasks.

5.3.1 Limitations

The presented approach is limited by the initial assumptions. Its physical faithfulness is limited by the fact that it is not based on spectral rendering. Using more sophisticated rendering might provide a more physical correct representation of the CA as it occurs in visual perception. In addition, a more sophisticated model of the eye, as used in model eyes for lens design (e.g., Weeber et al. (2008); Norrby et al. (2007)) might lead to more faithful renderings. Also, the assumption about the focus location based on the green colour channel might prove to be problematic. Other focusing mechanics, might result in different blur patterns, which could lead to different response sin the visual system.

5.4 Conclusion

Overall our investigation did not provide evidence that supports the idea that rendering a simplified model of GC CA results in improved depth perception or resolve the ambiguity problem inherent in DOF blur.

While we can not definitely conclude that there is no perceptual effect of physical accurate CA in depth perception. Overall, our data suggests that GC CA is might not be an easy way to resolve the problems inherent in GC DOF, and other approaches, for example, using it in conjunction with stereoscopic displays, might be more promising.

III

PART III

AUGMENTING
COLOUR
PERCEPTION

GAZE-CONTINGENT COLOUR MATCHING

At the most basic level, seeing means the sensing of light. From the light arriving at our eye to the final mental image of the world, the process of seeing involves, for example, the analysis of spatial frequencies, extraction of shapes and finally recognition of familiar shapes or objects. If this process can be supported, it stands to reason, that the largest impact can be had in the early stages. Colour, therefore, seem to make the ideal good starting point for investigating gaze-contingent manipulations on a basic level.

For a common display, the range of colours it can display is limited. A display is limited by the light it can produce and a printer by the light absorption properties of its ink as well as the illuminating light. The range of colours that can be produced is called its *gamut*. However, the colour a given area or object appears is affected by more than just the light that comes from the area itself. It is also influenced by the colour of its surround, for example, through simultaneous contrast (SC). That means while a medium might not be able to reproduce a colour on a neutral background, it can produce it if the surround is carefully chosen (see for example the simultaneous contrast example in Figure 2.11 from earlier).

This approach, however, is limited by the fact that the choice of the background colour influences the overall impression of the image. Using eye tracking this problem could be alleviated by changing the surround in

a dynamic way depending on the current gaze position. Every area of the screen could have its own surround colour, allowing it to be affected by SC individually. This could allow an expanded gamut for gaze-contingent displays (GCDs), but it also might affect the perception of the overall image in unexpected ways. It is also not clear whether this peripheral changes would induce SC in the first place or if it behaves similarly to static SC at all.

This chapter presents a first investigation into gaze-contingent manipulations of colour perception. It describes an approach that uses gaze-contingent manipulation of non-attended areas to influence how the currently attended colour (luminance as well as chromaticity) is perceived. This technique is evaluated in an empirical experiment that shows how the technique works compare to similar static presentation situations. The content of this chapter is based on parts of the paper Mauderer et al. (2016), which was done in collaboration with David Flatla and Miguel Nacenta.

A first step to show that manipulating the perceived colours with GCD techniques is feasible is to investigate how colour perception changes when colours are presented in a GC environment. In this case, the manipulation consists of changing the surround, as well as peripheral objects depending on the gaze position. A colour matching task is then able to detect if observers perceive different colours with or without these manipulations.

To detect the differences in colour perception participants manipulated the colour of a target patch to match a reference patch in both static and gaze-contingent conditions. From these results, we derived a measure of simultaneous contrast (the difference between matched colour for the same colour on varying backgrounds) and a direct colour comparison (the baseline of the observed colour). The experiment shows that the matched colours are similar in both gaze-contingent and static presentation in general but also found minor differences in the magnitude of the SC effect between the static and gaze-contingent conditions indicating that existing models might not perfectly predict colour perception on GCDs.

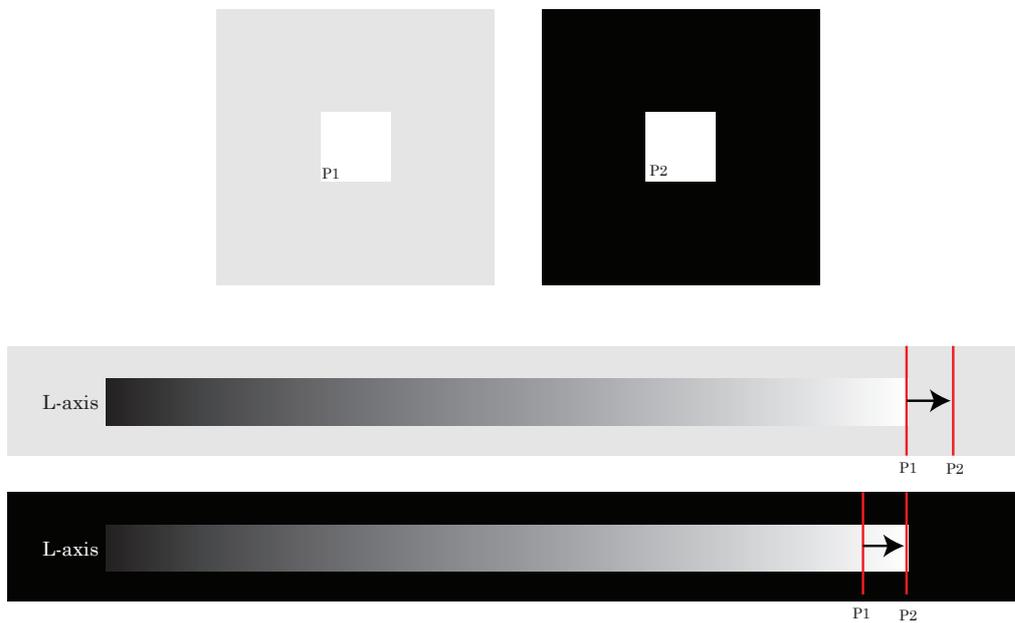


Figure 6.1: This schematic shows how the colour of the paper/display ("white") can appear different on different backgrounds and how this can lead to varying local gamuts. Even though there is no way of making an (achromatic) colour that is lighter than the pure white by changing the patch itself, it can be made to appear lighter by changing the background. Effectively, making the observer perceive a colour that would otherwise be out of gamut on the same background (as can be seen in the first L gradient). Effectively this means that the perceived colours can be shifted by pairing them with different backgrounds, extending the range of perceivable colours in a medium.

6.1 Goals and Research Questions

This chapter lays the foundation for the use of gaze-contingent displays to achieve a *perceived* gamut that is wider than what the same display could produce without gaze contingency. For example, consider the range of sRGB colours in the a^* axis (centre row, Figure 2.12). Existing knowledge of the simultaneous contrast effect Blackwell and Buchsbaum (1988) tells us that the green sRGB colour displayed at the left end of the a^* axis can be perceived equivalently (i.e., *matched* in a colour matching experiment) to a green further left on the axis (not displayed in the figure) *if a suitable surrounding colour is provided* for the original green. This will be called a *colour shift*. For example, the left-end green can be made to appear more green by surrounding it with a contrasting colour (for example red) even

if the green being perceived or, more precisely, the green that we would have to generate to match our original green's perception is actually out of the gamut that the display can produce. In simplified terms, the more contrasting the surrounding colour is (the redder or further right in the a^* axis in our example), the further the SC models predict the colour will shift outside the existing gamut.

We can achieve this effect on static displays for a single colour by manipulating the colours in the surround to have higher chromatic contrast (e.g., make them more red in our green example above); however, to actually enlarge the perceived gamut of a display, we have to be able to manipulate the colours in the surround for any colour at the edge of the gamut. A gaze-contingent display could help us shift the surrounding colours according to the position of gaze. This can only work if the simultaneous contrast effect is robust to gaze-contingent changes in the display and for, example, does not require that the surround of peripheral colour patches remains static. This leads to the research question central to this chapter: Does gaze-contingent presentation of colour preserve the simultaneous contrast effect, and if so, to what extent?

6.2 Common Terminology and GC-Manipulations

Accurate reproduction of colour in this thesis requires calibrated media, for example, a colour-calibrated display or printer that has a gamut covering all the used colours. We give descriptions of colours in CIELAB coordinates. The experiment samples the colour space at two points of each of the CIELAB axes by testing the hypotheses with colours on the L^* axis at low and high values (dark and light greys), the a^* axis at the green (low) and red (high) ends, and the b^* axis at the blue (low) and yellow (high) ends (Figure 2.12 provides a reference). When testing each axis, the other axes stay at default values which are $L^*=50$ and $a^*=b^*=0$. This means that if we refer to a colour by just one of its values (e.g., $a^*=43$) its full coordinates are $L^*=50, a^*=43, b^*=0$, or $(50, 43, 0)$.

Ideally, the experiments would test the different manipulations at samples covering the whole CIELAB space at regular intervals, but this is unfeasi-

ble at this stage for a multi-technique comparison and is not necessary for a proof-of-concept.

In general, we investigate two types of gaze-contingent colour manipulations: background manipulation and peripheral patch manipulation. Background manipulation changes the colour of the background area(s) depending on which area is looked at, i.e., a global change in the scene. This will be used to explore inducing different degrees of simultaneous contrast in different areas of the screen. Unattended patch manipulations change the colour of patches that are not currently being looked at, i.e., a local peripheral change of specific objects. This will be used to explore increasing contrast between objects, for example, to make peripheral objects easier to differentiate from the attended one.

6.3 Colour Matching Experiment

The goal of this experiment is to test whether SC persists with the gaze-contingent presentation of colour when an object's colour or its background change while the object itself is unattended, that is, the measured gaze location is away from the object. To test this, we use a standard colour matching experimental paradigm and compare several GC presentation conditions to a static one. We hypothesise that:

H1.1: Gaze-contingent simultaneous-contrast presentations of colour patches will result in colour shifts of the matched colours.

H1.2: Colour shifts of the matched colours will be similar in GC conditions and the static condition.

Rejecting H1.1 implies that GC-SC is not a useful technique to support perception. H1.2 tells us whether we can use existing CAMs (e.g., Hunt (1987, 1994)) to predict the colour appearance when performing gaze-contingent changes.

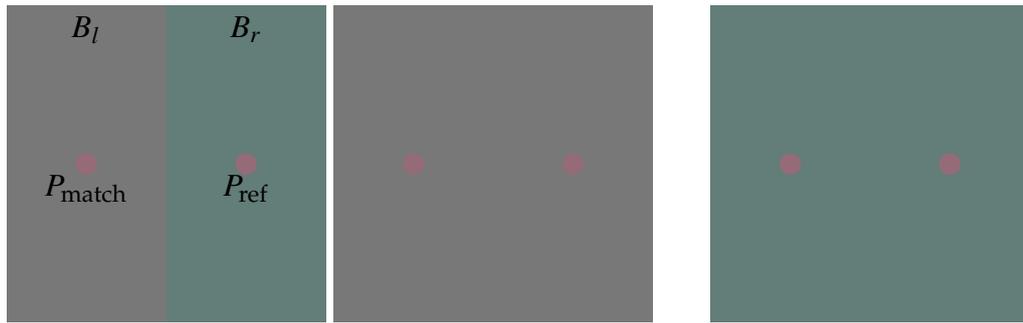


Figure 6.2: Example stimuli from Exp. 1. Left shows a static trial; each patch has its own background. Centre and right show a GC trial with the left (matching) patch and the right (reference) patch being attended.

6.3.1 Stimuli & Task

In each trial, the display contained two circular colour patches: the reference patch on the right P_{ref} and the adjustable matching patch on the left P_{match} . Each patch had a local background colour (B_l and B_r) (see Figure 6.2). The area around the image was white (the display white point). Each colour patch had a diameter of 2° visual angle and the patches were separated by 15° visual angle. Each half of the background had a width of 15° horizontally and 30° vertically.

The participants solved a colour matching task common in colour appearance research (e.g., Hunt (1952); Fairchild (2013)). The participants used a physical slider to control the colour of P_{match} until it matched the appearance of P_{ref} . The available colour range controlled by the slider depended on the trial (e.g., a range from green to red for a^* trials). The experiment contained instruction for the participants to compare the appearance of the patches by directly looking at them. We confirmed that the instruction was followed through the collected eye-tracking data and then performing a visual analysis of the gaze patterns for each participant to detect anomalous gaze behaviour, i.e., an above average number of fixations between patches instead of on patches.

6.3.2 Experimental Design & Manipulations

We chose five experimental factors in a $3 \times 2 \times 2 \times 2 \times 3$ design with a single repetition per participant, resulting in a total of 1728 trials (72 per participant). These factors controlled the appearance and behaviour of

the stimuli as follows:

Colour Space Axis (C_{dim}) – To provide a degree of generality each of the three axes of CIELAB is presented separately. That means that each trial shows colours from only one axis, while the other dimensions are set to their neutral (50 for L^* , 0 for a^* and b^*) value. Colours in one trial were thus either reddish/greenish (a^*), yellowish/blueish (b^*) or greys (L^*).

Reference Patch Colour (C_C) – For each axis, participants matched colours at one of the two ends of the given axis. The reference patch colours are called “low” and “high”, describing their location along the axis. The two values are equidistant to the centre value in CIELAB space (50, 0, 0), but were not at the very edge of the display gamut for methodological reasons; if the perceived reference colour was shifted outside the display’s physical gamut, the display would not be able to show a range that contained a match. The colour values used were 42.18 (■) and 57.81 (■) for L^* , and -20 (■ / ■) and $+20$ (■ / ■) for a^* and b^* .

Reference Patch Background Colour (C_B) – To manipulate the reference patch colour’s appearance through SC, the colour of its background was changed. The background could be one of two colours from within the range defined by the two reference extremes on each axis (as described in the previous paragraph). One of these background colours was near to the reference colour and one was far, enabling the experiment to differentiate between different levels of simultaneous contrast intensity (e.g., background colours that are more distant should shift the perceived reference colour more strongly away from the background colour, towards the outside of the gamut). The background colours were 46.09 (■) and 53.91 (■) for L^* , and -10 (■ / ■) and $+10$ (■ / ■) for a^* and b^* , respectively.

Background Manipulation (B_M) – This factor compared two presentation modes for the background: *static* and *gaze-contingent* (GC). In the static condition, the display was divided in the middle as shown in Figure 6.2. The background to the left (around the matching patch) was neutral (50, 0, 0) and the background to the right had the reference patch background colour. In the GC background condition, B_l and B_r had the same colour resulting in a uniform background, but the colour varied with

the participant's gaze location. When looking at (or to the right of) the reference patch, the background had the *reference patch background colour* and when looking at (or to the left of) the matching patch, the background was neutral grey. When looking between the patches the background colour was linearly interpolated between the reference patch background colour and the neutral grey. The interpolation process is illustrated in Figure 6.3.

Reference Patch Manipulation (C_δ) – So one of the assumptions was that that viewers switch gaze between the reference patch and the matching patch to compare colours and that they use their impression of the colour of a patch while it is centred on the fovea to accomplish the matching task; however, it is also possible that viewers use information from their peripheral vision to perform matching. To control for this possibility, this manipulation affects the colour of the reference patch by an offset C_δ when unattended (by adding the offset to the CIELAB coordinate). The colour of the patch was linearly interpolated between its base value and the modified value (base value + offset) as in the Background Manipulation above. There are two different values for the offset, one negative and one positive (both along the trial's axis), resulting in three possible levels of C_δ : one negative, one zero (static) and one positive. The values used for L^* , a^* and b^* respectively are: $-3.91/+3.91$, $-10/+10$, $-10/+10$. An exemplary visual representation of the change and interpolation can be seen in Figure 6.3.

6.3.3 Apparatus

We used a monocular EyeLink 1000 eye tracker that provided gaze data at 1000 Hz with a nominal 1.4 ms delay. The tracker was installed in a tower mount configuration with a chin rest that kept the participant's face at a stable distance from the screen (40 cm).

The display was an Iiyama HM204DT 22 inch CRT display with a resolution of 1280 px \times 1024 px running at 100 Hz. We calibrated the colour output of the screen by using a PR-650 SpectraScan spectroradiometer to measure the screen through the eye tracker's hot mirror. We took measurements for the white point, R/G/B primaries and 25 luminance values along each R/G/B channel. These values were used to create

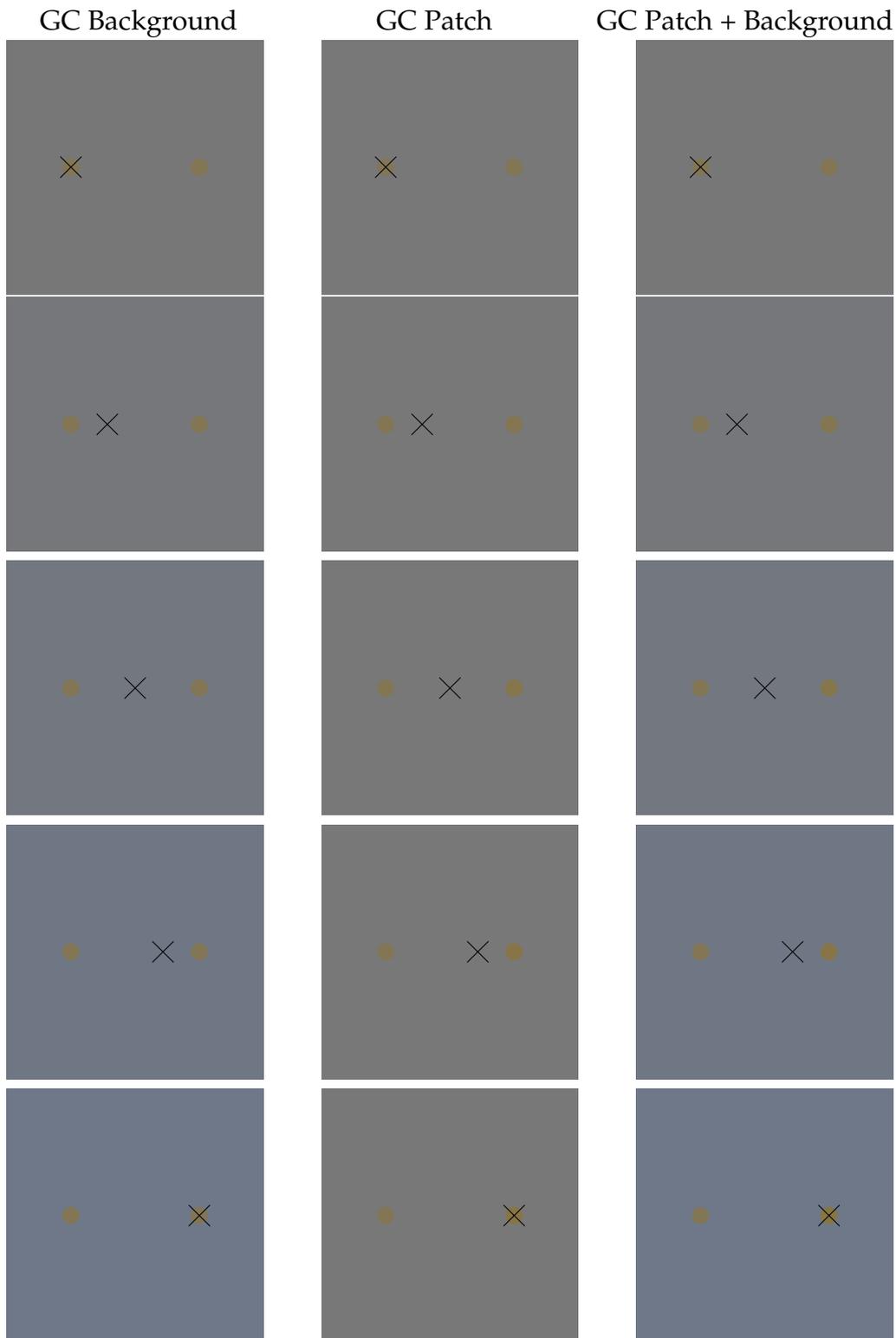


Figure 6.3: Examples of gaze-contingent colour manipulation techniques and interpolation functions. Each column shows (top to bottom) five frames of display changes while the observer's gaze moves from the left to the right patch. In the left column, the background changes colour, in the middle column, the right patch changes its colour and in in the right column both patch and background change colour.

a monitor calibration profile for PsychoPy¹, ensuring linear luminance values along each R/G/B channel, as well as a monitor-specific RGB colour space specification for colour computations.

Participants controlled the matching patch colour through a custom-built physical input slider and a capacitive plate that served as a button to confirm input. The slider controlled the colour along the current axis (e.g., the slider made the matching patch go between green and red when testing a^* , blue and yellow when testing b^* , and between dark and light when testing L^*).

The experiment took place in a darkened room with the area surrounding the display covered with a matte black surface to avoid visual distraction from the monitor's front plate.

The experimental software was built using PsychoPy (Peirce, 2009) and colours were calculated using Colour (Mansencal et al., 2015).

6.3.4 Participants

24 participants (15 female, aged 18 to 65, $M=25.54$, $SD=10.66$) took part in the experiment. All had a normal or corrected-to-normal vision, 14 were right-eye dominant, 19 were right-handed. Eye dominance was determined using the Miles test, acuity with a Snellen chart, and absence of colour vision deficiency with the Ishihara test using hidden digit plates. An additional six participants were tested but excluded from the analysis due to severe problems with the eye-tracking, that is, no working calibration was possible, or the calibration deteriorates throughout the experiment. Another participant was excluded because they did not follow the experimental instructions.

6.3.5 Procedure

After participants received a brief introduction and provided written ethical consent to the experiment (in compliance with the local committee), the participants answered a demographic questionnaire and performed the vision tests. Then participants performed a five-point gaze-calibration procedure followed by a tutorial which explained the basic task. The

¹<http://www.psychopy.org/general/monitors.html>

time spent on the tutorial and calibration provided some time (about 5 to 10 minutes) for adaptation to the screen before the main experiment, allowing for full chromatic adaptation to the display white-point (Fairchild and Reniff, 1995).

Each trial began with a fixation cross in the centre of the screen and started when the participant looked at it. The participant controlled the matching patch's colour with the slider according to our instructions. Once a trial was complete, the participant had to reset the slider position to the bottom of the input device before proceeding to next trial.

Trial order was randomised for each participant. After half the trials, there was a break. After the break, we checked the eye tracker calibration for changes in accuracy and re-calibrated if the average error was more than 1 degree. No change in room lighting happened during the break. The experiment took about 60 minutes. After the participants had completed all trials, they received debriefing information and compensation.

6.3.6 Measures and Statistical Analysis

The main raw measure for each trial was the CIELAB coordinate of the matching patch colour along the given axis, which was recorded along with the specific condition (i.e., the reference patch colour and its manipulations). We also recorded gaze patterns to validate participant behaviour.

To detect SC, we derived a measure called *simultaneous contrast effect* (ΔC) calculated as the difference (in CIELAB units) between the colours matched for a given reference colour when using the two different backgrounds of the *reference patch background colour factor* (C_B). This value will be non-zero if SC exists as different background colours will have changed the appearance of the reference patch colour.

For completeness, we also derived a measure called *absolute colour appearance* (\bar{C}) which was the average across both background colours (C_B) of the matched colour (all other conditions being equal), giving an SC-independent measure. This allows me to make simple comparisons in CIELAB units between conditions (for H1.2). For example, by looking at absolute colour appearance, we can learn how much more green the green

reference patch appears in the GC condition than in the static condition.

There are some severe outliers that appeared to be caused by resetting the slider before confirming the input. To address this, we trimmed the data to 3σ in each cell, affecting 17 trials ($\sim 1\%$ of all trials).

6.3.7 Results

We report results by measure: simultaneous contrast effect (ΔC) and then absolute colour appearance (\bar{C}).

6.3.7.1 Simultaneous Contrast Effects

We analyse ΔC per axis. Large ΔC values indicate a large shift in matched colour due to SC. Results of the omnibus RM analysis are summarised in Table 6.1. The intercept of the model has a special meaning because it shows whether SC appeared at all.

6.3.7.2 L* Axis

The large effect size of the intercept for the L* axis ($M = -3.56$ CI $[-3.81, -3.30]$) indicates that SC is present overall. All other factors and interactions have small effects. This means that the static and gaze-contingent manipulations are not sufficiently different in terms of SC effects to result in an interaction. There are no large effect sizes in factors or interactions related to gaze-contingent manipulations. This is evidence that gaze-contingent manipulations did not negate simultaneous contrast.

There is a small effect for the interaction $B_M \times C_C$, which could indicate a systematic (if small) difference between GC and static background manipulation for specific colours. The GC condition has a larger SC effect than the static condition for the dark end of the L* axis (Figure 6.4). The effect sizes for the GC-vs-static difference are $M_D = -1.1$, $d_{\text{diff}} = -0.43$ for low and $M_D = -0.12$, $d_{\text{diff}} = -0.050$ for high.

6.3.7.3 a* Axis

Results on the a* axis are similar to those on the L* axis. The intercept (the measure of SC effect) is weaker than in L* (although clearly present $M = -3.43$ CI $[-4.22, -2.69]$).

6.3. Colour Matching Experiment

Factors	df	\tilde{df}	F	p	η_p^2
<i>Results for L*</i>					
(Intercept)	1.00	22.00	219.52	<0.01	0.75
B_M	1.00	22.00	4.93	0.04	0.03
C_C	1.00	22.00	0.40	0.53	<0.01
C_δ	2.00	44.00	0.68	0.51	<0.01
$B_M \times C_C$	1.00	22.00	5.17	0.03	0.02
$B_M \times C_\delta$	2.00	44.00	2.63	0.08	0.01
$C_C \times C_\delta$	2.00	44.00	0.12	0.89	<0.01
$B_M \times C_C \times C_\delta$	2.00	44.00	3.26	0.05	0.01
<i>Results for a*</i>					
(Intercept)	1.00	22.00	44.04	<0.01	0.24
B_M	1.00	22.00	1.33	0.26	<0.01
C_C	1.00	22.00	12.98	<0.01	0.11
C_δ	1.51	33.25	1.99	0.16	<0.01
$B_M \times C_C$	1.00	22.00	0.29	0.59	<0.01
$B_M \times C_\delta$	2.00	44.00	0.06	0.95	<0.01
$C_C \times C_\delta$	2.00	44.00	0.56	0.57	<0.01
$B_M \times C_C \times C_\delta$	2.00	44.00	0.91	0.41	<0.01
<i>Results for b*</i>					
(Intercept)	1.00	22.00	198.78	<0.01	0.56
B_M	1.00	22.00	4.47	0.05	0.02
C_C	1.00	22.00	45.58	<0.01	0.22
C_δ	2.00	44.00	1.33	0.27	<0.01
$B_M \times C_C$	1.00	22.00	12.92	<0.01	0.05
$B_M \times C_\delta$	2.00	44.00	0.23	0.79	<0.01
$C_C \times C_\delta$	2.00	44.00	2.37	0.10	0.02
$B_M \times C_C \times C_\delta$	2.00	44.00	0.59	0.56	<0.01

Table 6.1: Results of the repeated measure ANOVA of simultaneous contrast effect in Experiment 1, split by CIELAB axis.

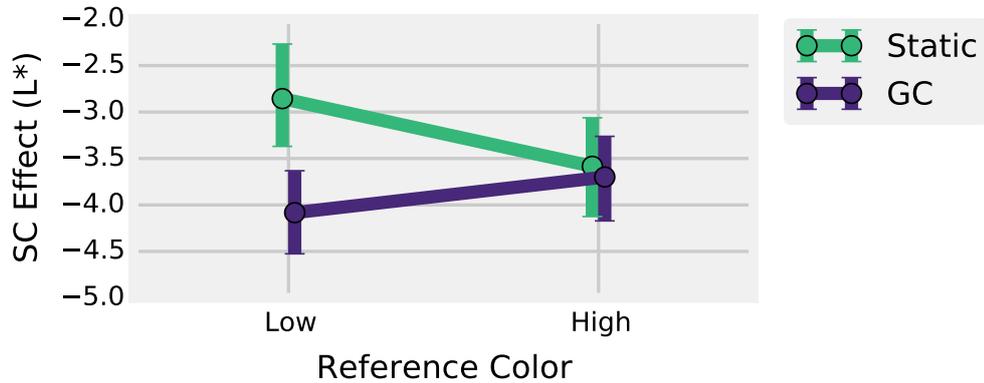


Figure 6.4: Plot of the $B_M \times C_C$ interaction on the L^* axis for SC effect.

As in L^* , GC-related factors show no effects.

The effect on C_C simply shows that SC is not homogeneous along the axis, a result in agreement with existing CAMs.

6.3.7.4 b^* Axis

The SC effect is also evident in the b^* axis through the intercept with $M = -7.28$, $CI[-8.17, -6.37]$. As in a^* , the C_C effect shows that SC varies on both ends of the axis.

In b^* there are two interactions with small effect sizes. $B_M \times C_C$ and $C_C \times C_\delta$ are plotted in Figure 6.5. The former shows that the SC effect is slightly reduced in the GC condition for the high colour case $M_D = 4.7$, $d_{diff} = 0.47$. The latter, which suggests that different values of peripheral offset (C_δ) affect the low and high ends of the axis differently, is probably of little practical importance judging from the CIs and the small differences.

6.3.7.5 Absolute Color Appearance

This section looks at the \bar{C} measure, which ignores the SC contrast effect to focus on absolute colour appearance shifts. Results of the omnibus RM analysis are summarised in Table 6.2. The large effect of C_C is trivial since if the display shows a different colour, people will match it to a different colour.

Across all axes there also is a small but consistent main effect of the peripheral gaze-contingent manipulation (C_δ). Participants matched

6.3. Colour Matching Experiment

Factors	df	\tilde{df}	F	p	η_p^2
<i>Results for L*</i>					
<i>(Intercept)</i>	1.00	22.00	506881.52	<0.01	1.00
B_M	1.00	22.00	0.95	0.34	<0.01
C_C	1.00	22.00	5158.22	<0.01	0.98
C_δ	2.00	44.00	8.20	<0.01	0.06
$B_M \times C_C$	1.00	22.00	1.21	0.28	<0.01
$B_M \times C_\delta$	1.48	32.48	0.78	0.43	<0.01
$C_C \times C_\delta$	2.00	44.00	0.28	0.75	<0.01
$B_M \times C_C \times C_\delta$	2.00	44.00	1.05	0.36	<0.01
<i>Results for a*</i>					
<i>(Intercept)</i>	1.00	22.00	1.76	0.20	0.01
B_M	1.00	22.00	0.02	0.88	<0.01
C_C	1.00	22.00	3532.09	<0.01	0.98
C_δ	2.00	44.00	6.34	<0.01	0.04
$B_M \times C_C$	1.00	22.00	1.62	0.22	<0.01
$B_M \times C_\delta$	2.00	44.00	1.43	0.25	<0.01
$C_C \times C_\delta$	1.60	35.21	0.73	0.46	<0.01
$B_M \times C_C \times C_\delta$	2.00	44.00	0.02	0.98	<0.01
<i>Results for b*</i>					
<i>(Intercept)</i>	1.00	22.00	4.01	0.06	0.02
B_M	1.00	22.00	0.79	0.38	<0.01
C_C	1.00	22.00	2441.87	<0.01	0.97
C_δ	2.00	44.00	6.00	<0.01	0.03
$B_M \times C_C$	1.00	22.00	1.53	0.23	<0.01
$B_M \times C_\delta$	2.00	44.00	5.22	<0.01	0.02
$C_C \times C_\delta$	2.00	44.00	2.50	0.09	0.01
$B_M \times C_C \times C_\delta$	2.00	44.00	0.27	0.77	<0.01

Table 6.2: Results of the repeated measure ANOVA of absolute colour appearance, split by CIELAB axis.

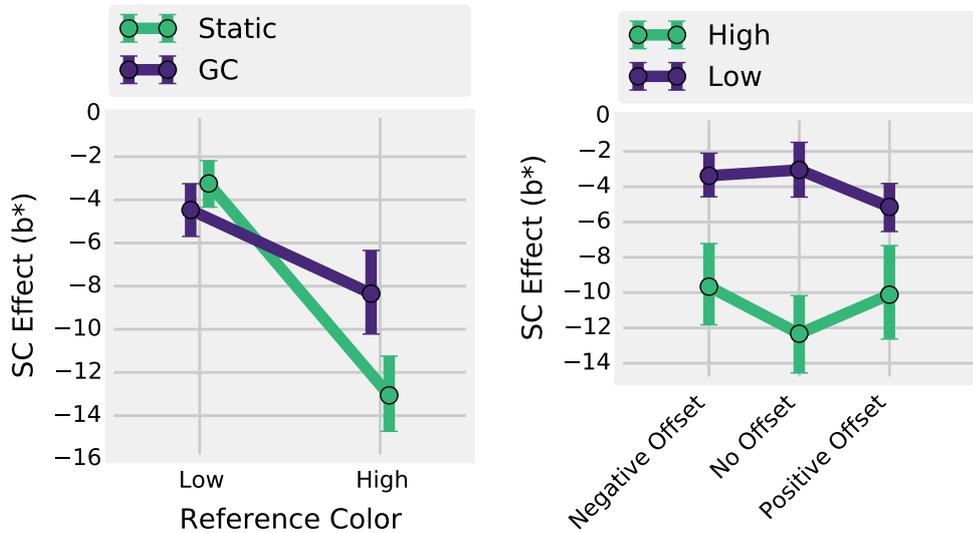


Figure 6.5: Plots of the interactions observed for the simultaneous contrast effect in the b^* axis. $B_M \times C_C$ (Left), $C_C \times C_\delta$ (right).

their stimulus with a small influence of peripheral colour change (see Figure 6.6).

There are two small interactions in the b^* axis that involve C_δ : the first one with C_C and the second one with B_M (Figure 6.6). The difference between C_δ positive and negative persisted, but the no-offset condition seemed to deviate for C_C high and B_M GC. These findings show that there are exceptions to the effect of C_δ in very specific conditions.

6.4 Discussion

The strong effect sizes of the intercept for all axes indicate that the experiment was able to replicate the simultaneous contrast effect and, more importantly, that gaze-contingent presentations of the stimuli cause simultaneous contrast as well (H1.1 is supported). Looking at the magnitudes of the SC effect achieved (3.56, 3.43 and 7.28 for the CIELAB axes respectively) we can estimate how much larger a gamut would be if we could achieve these results at the edge of a gamut. Taking the restricted gamut of the experiment, where the CIELAB axes have a length of 15.63, 40 and 40 respectively as a base and assuming this effect could be achieved equivalently to all the edges of the gamut used in the experiment, this

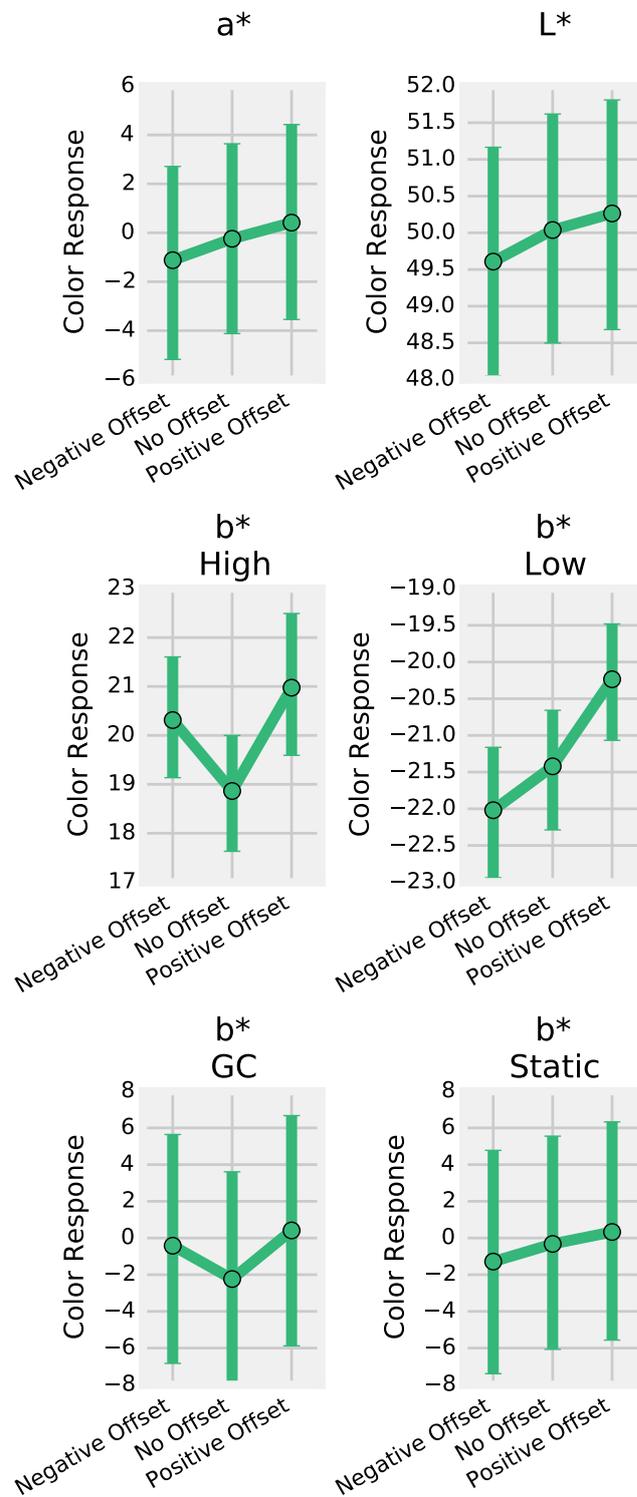


Figure 6.6: Plots of baseline colour response modulated by C_δ . From left to right the results are for the a^* axis, the L^* axis, followed by the b^* axis split by C_C (high and low) and then the b^* column split by B_M (GC and static).

would translate to an average increase of 33% of range along each axis and therefore potentially more than doubling the gamut volume.

The results also show some small differences between gaze-contingent and static presentation, but only in the b^* axis. H1.2 is consequently only partially supported; there are systematic effects that might prevent us from applying current SC models directly to GC SC. This might be caused either, by peripheral influences when comparing colours, made especially feasible by the fact that cones sensitive to blue are more dense in the periphery.

The experiment shows that changing the reference colour patch while in the periphery (reference patch manipulation) can also produce shifts in the matched colour. Although these shifts are small compared to the SC effect and are modulated by the patch's colour, they deserve further exploration. They open an interesting possibility of gaze-contingent manipulation which the following chapter explores.

In addition to insights into the gaze-contingent presentation, the results also show that SC does not take place uniformly across the CIELAB space. One might be tempted to think that since CIELAB is designed to be perceptually uniform, SC would happen uniformly across the space as well; however, our data provides additional evidence that this is not the case.

6.4.1 Limitations

Because this investigation has been conducted as a controlled laboratory experiment, it might lack ecological validity. The results and techniques are designed as a first starting point into the area of gaze-contingent colour manipulation, providing insights into basic perceptual properties. They provide basic data that can be used to inform future development of more complete algorithms for practical applications that use high-resolution images, containing continuous image data, instead of abstract and discrete colour patches.

While the goal was to investigate whether it is possible to extend the gamut of a device, the range of colours in the experiment was artificially limited. This was done to make it feasible to provide a simple colour

matching interface on the same device that also reproduced the colours. Future research will have to show that this technique can be used for more typical gamut sizes, for example, using an HDR display and restricting the gamut to an LDR range, or using other devices/objects for matching.

6.5 Conclusion

This chapter presented an empirical evaluation of gaze-contingent manipulation of colours through simultaneous contrast and peripheral object colour manipulation. The experiment provides insight into general perceptual properties and benefits of gaze-contingent colour presentation. The results show that gaze-contingent simultaneous contrast can be used to change the appearance of colours, which could be used to extend the perceived gamut of a display. This creates the foundation for further applications, for example, to support tasks that require the differentiation of similar colours, which are investigated in the following chapter.

GAZE-CONTINGENT COLOUR DISCRIMINATION

The investigation from the last chapter has shown that it is possible to use gaze-contingent manipulations of surround colours to affect the perceived colour. This chapter shows how this can be applied to provide a benefit in a task that requires colour discrimination: colour sorting. It presents the design and implementation of an experiment in which participants sorted coloured patches into a gradient using both static and gaze-contingent presentation techniques.

The results show that gaze-contingent techniques allowed participants to sort colours with fewer errors than in the naive static condition, although through a technique that is not directly based on the manipulation of simultaneous contrast. This technique could be used in information visualisations that use colours to encode categories to increase the number of categories that can be differentiated.

The content of this paper is based on parts of the paper Mauderer et al. (2016), which was done in collaboration with David Flatla and Miguel Nacenta.



Figure 7.1: Example of stimulus setup. Relatively high-contrasting L^* axis colours are shown for illustrative purposes; differences between patches were much subtler in real trials.

7.1 Colour Sorting Experiment

This experiment investigates if gaze-contingent (GC) techniques (simultaneous contrast and the peripheral colour adjustment discussed in the previous chapter) can enhance colour discrimination. Although the last chapter showed that GC manipulations could be used to shift how a colour is perceived, this experiment now considers whether this can be leveraged to increase the differentiability of colour steps perceived by viewers, thus providing a clear perceptual benefit over static presentation. To test this, participants solve a gradient sorting task similar to a Farnsworth-Munsell 100 hue test (Farnsworth, 1943). This task can show that:

H2.1: Gaze-contingent simultaneous contrast presentation of colour will result in fewer errors in the ordering of the sequences.

H2.2: Peripheral manipulation of colours will result in fewer errors in the ordering of the sequences.

If either H2.1 or H2.2 is true, this supports the overall thesis that manipulating colours can support the user's perception, in this case, to differentiate between colours that look very similar.

7.1. Colour Sorting Experiment

Colour Patch Gradients						
	L*		a*		b*	
	low	high	low	high	low	high
Lower	39.10 	54.19 	-23.84 	16.16 	-23.84 	16.16 
Upper	45.10 	60.19 	-16.16 	23.84 	-16.16 	23.84 
$\Delta_{CIE2000}$	5.44	5.50	4.59	4.59	4.04	4.04

(a) Gradient values used for the colour patches

Background Gradients			
	L*	a*	b*
Lower	45.50 	-5.76 	-5.76 
Upper	54.50 	5.76 	5.76 
$\Delta_{CIE2000}$	9.00	10.62	15.97

(b) Gradient values used for the backgrounds

Table 7.1: Colour Gradients used in the colour sorting experiment and $\Delta_{CIE2000}$ differences between them. Values denote upper and lower ends of the gradients along the relevant colour axis in CIELAB space. Intermediate values were interpolated linearly. Colour swatches provided for illustration might not correspond to the exact colour displayed in the experiment, and can vary depending on viewing medium.

7.1.1 Stimuli & Task

The stimuli in this task consisted of eight square colour patches, each covering $2^\circ \times 2^\circ$ visual angle. The patches were placed horizontally with a gap separation of 2° (see Figure 7.1) within a square background of $35^\circ \times 35^\circ$. Outside of this area, the display was white. The patch colours were from a gradient of similar colours (see Table 7.1). The leftmost and rightmost patches were fixed in position and showed the colour extremes. The other patches could be re-arranged via mouse input using drag-and-drop.

The task was to arrange the patches from left to right according to their colour so that they formed a gradient between the fixed patches at the extremes. Accuracy was measured through an error score taken from the original Farnsworth task (Farnsworth, 1943). While dragging, a patch was not shown to move, as this would allow the participant to move patches

next to each other for comparison. Instead, the square was replaced by a black outline that would only indicate the current position. After moving a patch, a small white line below the patch flashed to indicate the change. This reassured participants that changes had occurred when they were working with very small colour differences.

To score the result, each patch was assigned a number according to its actual position along the gradient. For each patch in the participant-determined order, we added the absolute difference of the patch's number with the numbers of the patches on its left and right, subtract two, and then summed the sub-scores for all patches. A perfect order gives a score of zero.

At the start of the trial the patches appeared in a randomised arrangement with an error score of 21. This kept the baseline error score sufficiently high and consistent between participants and avoided varying difficulty between trials.

7.1.1.1 Colour Gradients and Backgrounds

As in the previous experiment, we sampled along each CIELAB axis. The exact gradients are described in Table 7.1. The gradients contained very similar colours that were hard to distinguish. If the task had been too easy the different manipulations would not show differences due to ceiling effects. $\Delta_{CIE2000}$ (a measure of perceptual differences) of the extremes of the gradient was about 5, where a value of 1 corresponds approximately to a *just noticeable difference*.

Each gradient had a corresponding background gradient (also in Table 7.1) for the GC-SC manipulation. To choose these, we balanced the goal of maximising simultaneous contrast effects (according to the data that we obtained from the previous experiment) while keeping the experiment simple (by using a single background gradient for both ends of the axis). These background gradients were thus chosen to be broad but centred around the middle point of each axis.

7.1.2 Techniques

We tested five different colour presentation techniques. These corresponded to all combinations of absent or present manipulations of the background (i.e., the simultaneous contrast manipulation) and the peripheral object colour manipulation, plus an additional static technique that served as control.

Static (S_u) – This was the baseline, with no manipulations. It displayed the colour gradient on a background of static uniform middle grey ($L^*=50$, $a^*=0$, $b^*=0$).

GC patches (GC_{patch}) – Peripheral patches changed their colour to increase contrast in relation to the currently attended patch. we used this function to compute the colours to display:

$$r(c_i) = \begin{cases} c_i & \text{for } i = i_a \\ \text{interp}(c_0, \max(c_0, c_a - \Delta c), \frac{i}{i_a}), & \text{for } i < i_a \\ \text{interp}(\min(c_7, c_a + \Delta c), c_7, \frac{i-i_a}{7-i_a}), & \text{for } i > i_a \end{cases}$$

where $r(c_i)$ is the resulting $L^*/a^*/b^*$ value for the current trial, c_i is the colour along the gradient at index i (c_0 is the lower end of the gradient and c_7 the upper end), i_a is the colour index of the currently attended patch, $\text{interp}(a,b,x)$ is a linear interpolation function at x (in $[0, 1]$) between $(0, a)$ and $(1, b)$, and Δc is a constant value that depended on the CIELAB axis (3 for L^* and 3.84 for a^* and b^*). See Figure 7.3 for an example of this condition and Figure 7.2 for a visualisation of the function.

Since the distance between patches is very small, we chose not to use continuous interpolation for gaze position between patches. Instead, we implemented a hysteresis-based approach; a patch would only be considered attended once the gaze position was measured inside of its visible area on the screen. This means that if the participant looked between two patches, the colours would remain unchanged until the gaze was measured to be inside of the new patch.

GC background (GC_{bg}) – This technique changed the background based on the attended patch, i.e., it applied simultaneous contrast. The colours for the background of each patch were determined from the gradients

7. GAZE-CONTINGENT COLOUR DISCRIMINATION

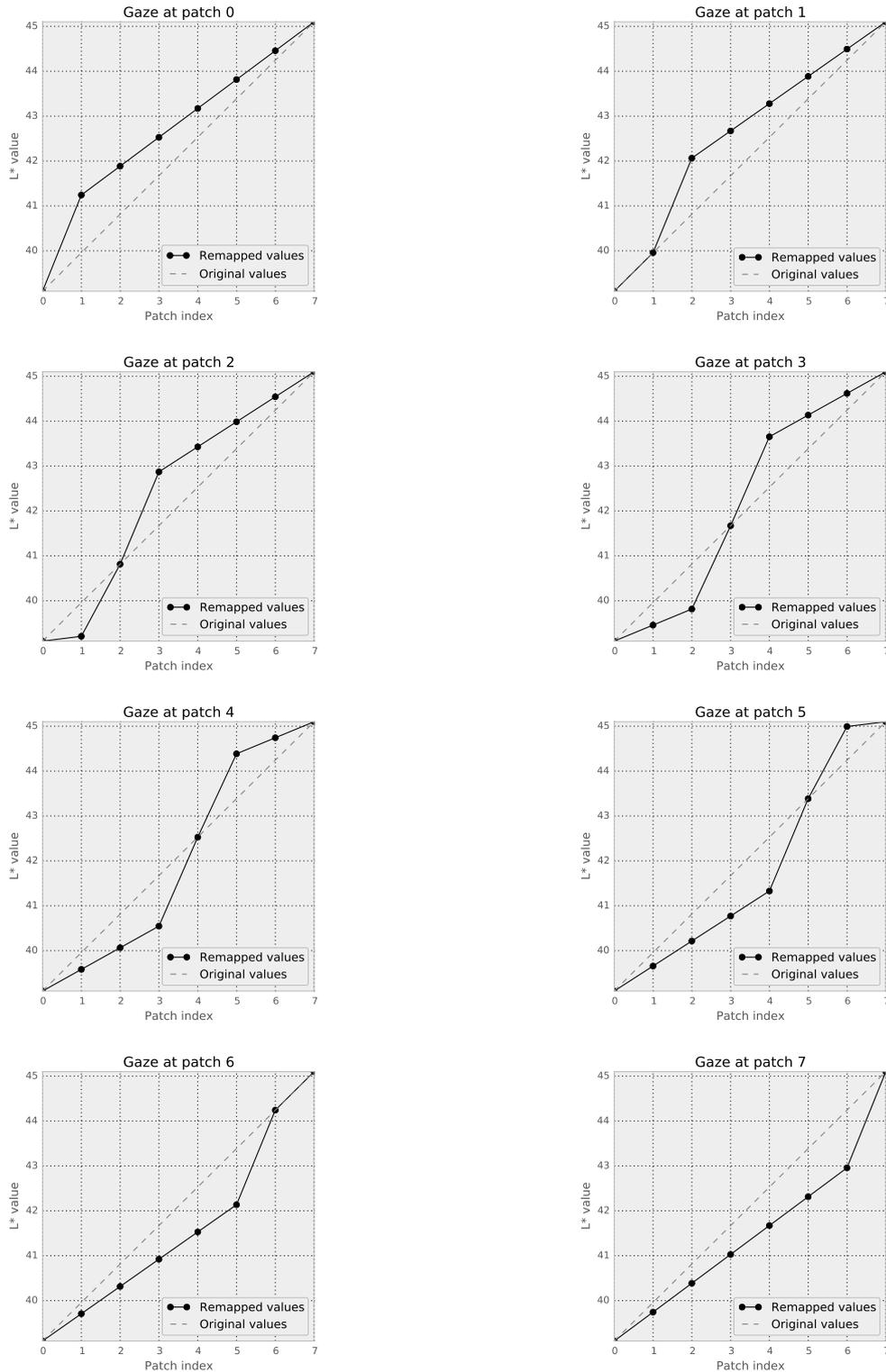


Figure 7.2: Visualisation of the contrast enhancement function for colour patches. The plots show the relationship between the the L* values of an example gradient in different states based on the gaze position. The indices indicate the patch position along the correct gradient, which is independent of the actual current position. The unattended colours are made more dissimilar to the attended colour, at the cost of contrast in between them.

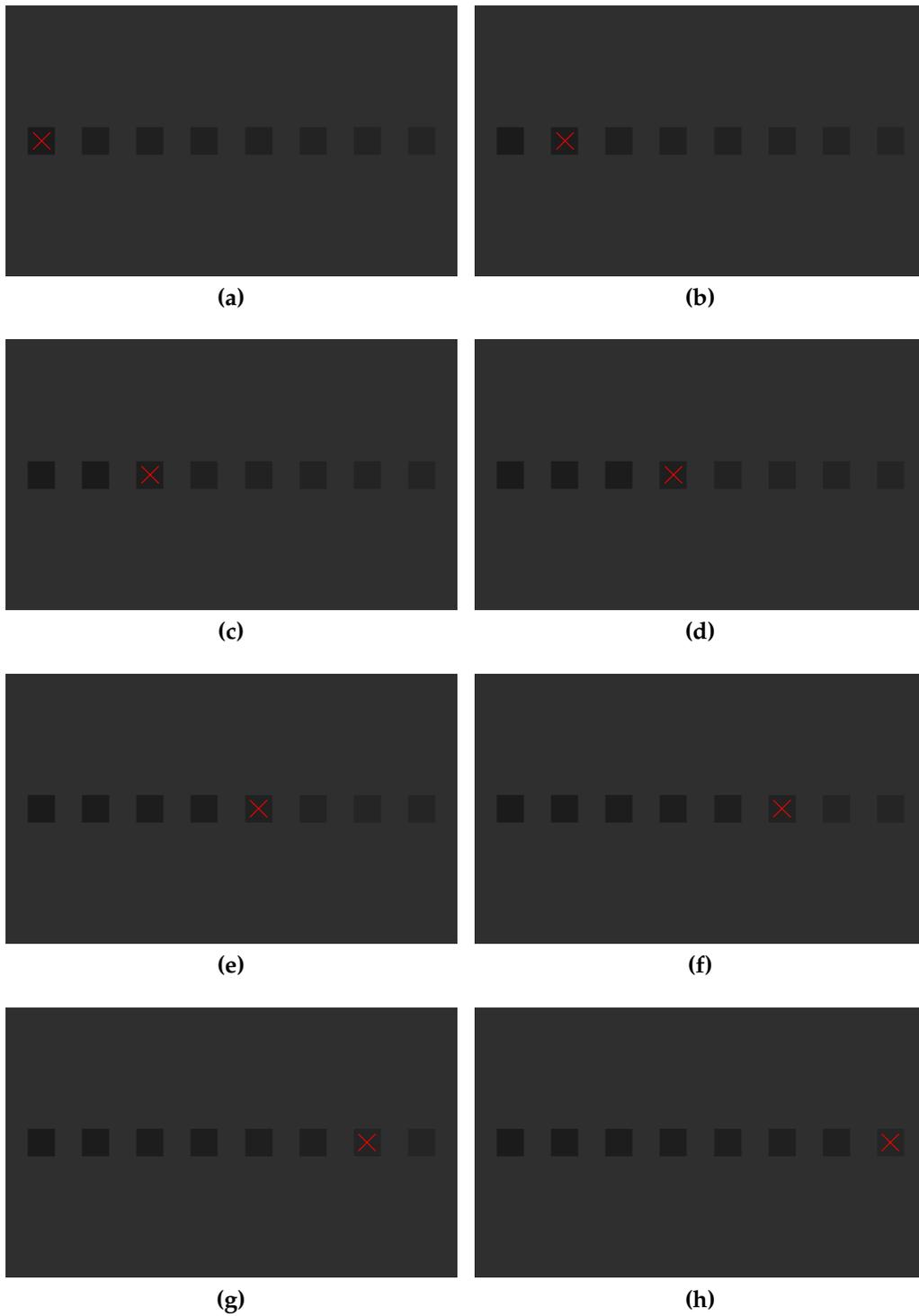


Figure 7.3: Examples screen crops from experimental condition GC_{patch} where the patches are already correctly ordered. Each example shows the state for the gaze position that is indicated by the red cross. The unattended patches are made to appear more dissimilar to the currently attended one. It can be seen that the patches to the left of the attended patch are darker, the ones to the right lighter.

described above. The currently attended patch was determined in the same way as in GC_{patch} . An example of this condition can be seen in Figure 7.4.

GC background and patches ($GC_{\text{bg+patch}}$) – This technique combined both GC_{patch} and GC_{bg} simultaneously.

Static with Frames (S_f) – This technique was similar to S_u , but each patch was enclosed by a 0.25° wide frame (see Figure 7.5 for an example). The colours of the frames were picked from the background gradient to enhance the difference between patches through SC. This technique provided SC-enhanced colour in a static form but is somewhat artificial because it is feasible only for specific spatial arrangements that allow the addition of frames, adds visual noise and is consequently of limited utility in realistic scenarios.

Consistent with the hypotheses, we expected the three gaze-contingent techniques to reduce errors compared to the baseline. We also suspected that the static with frames technique (S_f) would perform well due to the additional visual information included in the frame, which could be used in addition to the patch colour to inform ordering.

7.1.3 Experimental Design

The design was a $3 \times 2 \times 5$ (colour axis \times colour \times technique) within-subjects design with two repetitions per cell, resulting in 60 trials per participant. The presentation of trials was blocked by technique; block order was balanced between participants using Latin squares.

7.1.4 Apparatus

The apparatus is identical to the experiment from Chapter 6 except that, due to lab requirements for another experiment, the screen was replaced with an Iiyama MM904UT 19 CRT running at $1280 \text{ px} \times 1024 \text{ px}$ and 85 Hz. This setup was re-calibrated using the same procedure as the previous setup. The participants provided responses through a keyboard and mouse.

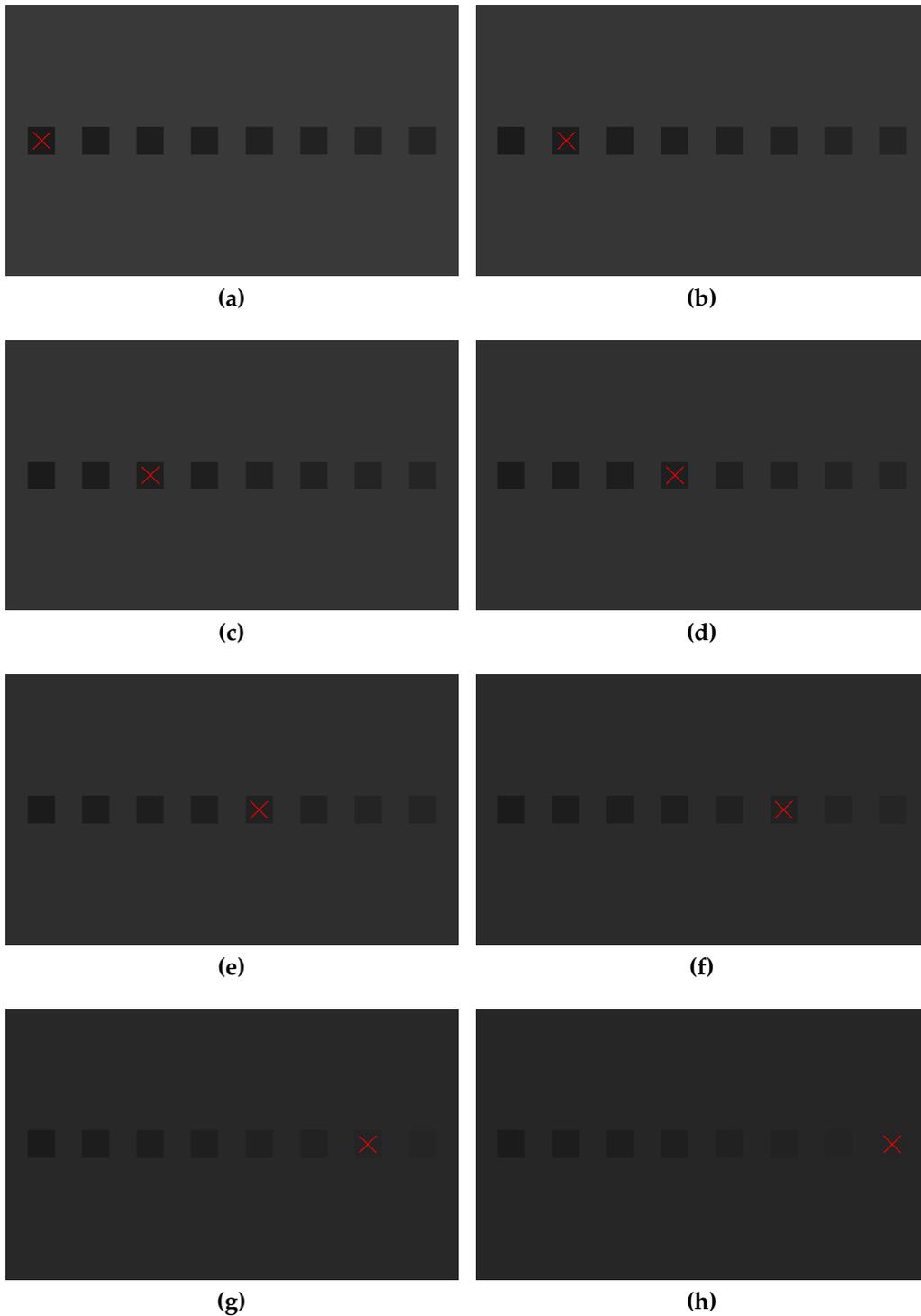


Figure 7.4: Examples screen crops from experimental condition GC_{bg} where the patches are already correctly ordered. Each example shows the state for the gaze position that is indicated by the red cross. The background changes with the aim to increase the perceived dynamic range of the patches.

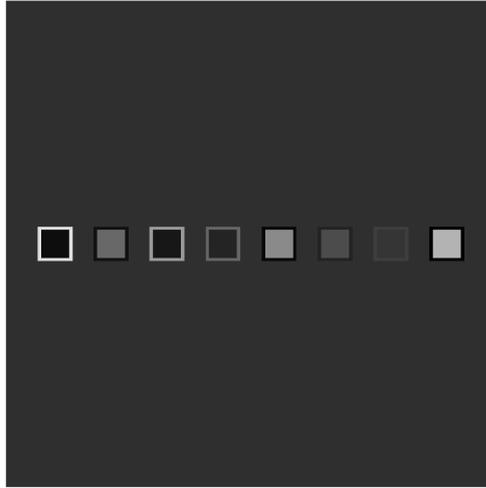


Figure 7.5: Example of stimulus setup in S_f condition.

7.1.5 Participants

We tested 20 participants (14 female, aged 18 to 39, $M = 23.85$, $SD = 6.32$, all had normal or corrected-to-normal vision, 15 were right-eye dominant, 16 were right-handed). Two participants were excluded from the analysis due to severe problems with their eye tracking.

7.1.6 Procedure

Participants gave written consent in compliance with the St. Andrews ethics regulations. We collected demographic information through a preliminary questionnaire and then performed the vision screening tests.

The participants then sat at the eye tracker, learned the task through a tutorial (four trials with easy black to white gradients), and performed a five-point calibration procedure. Each trial began when the participant was looking at a cross. After each block, there was a short break. After each break, we checked the calibration for changes in accuracy and recalibrated if the average error was more than 1 degree. The experiment lasted approximately 45 minutes.

7.1.7 Measures and Statistical Analysis

The main measure was the error score derived from the final configuration of the patches. The error responses were not expected to be normally

7.1. Colour Sorting Experiment

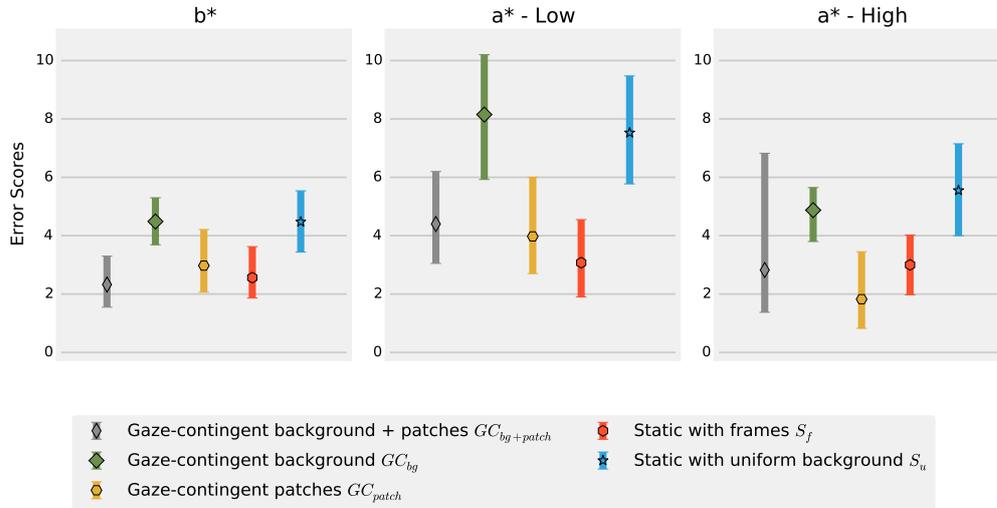


Figure 7.6: Error scores on the a^* and b^* axis for each technique.

distributed (skewed towards perfect performance). Although we use a parametric model for the omnibus test, the comparison analysis and the confidence intervals are computed using non-parametric bootstrapping that are robust against violations of normality.

7.1.8 Results

Table 7.2 shows the results of the RM-ANOVA. We focus on the *technique* factor, which is directly related to the hypotheses. The effect sizes of Technique on the number of errors are smaller than in the previous chapter, but still sizable in all axes (η_p^2 of 0.21, 0.61 and 0.56 for L^* , a^* and b^* respectively). This indicates that the different techniques affected accuracy and justifies further comparisons between techniques.

Unfortunately, when looking at error scores according to the axis, we found that performance with the L^* axis was close to perfect for most participants, despite its gradients having similar $\Delta_{CIE2000}$ ranges to the other axes. This ceiling effect masks the differences between techniques, making pairwise comparisons uninformative; therefore, we omit the L^* axis in the following analysis.

The performance of the individual techniques in the a^* and b^* axes (Figure 7.6) reveals a clear pattern: in both axes, the S_u and GC_{bg} condition had the highest error scores, while the three other techniques had low

7. GAZE-CONTINGENT COLOUR DISCRIMINATION

Factors	df	\tilde{df}	F	p	η_p^2
<i>Results for L*</i>					
<i>(Intercept)</i>	1.00	19.00	25.77	<0.01	0.21
<i>Color</i>	1.00	19.00	<0.01	0.97	<0.01
<i>Technique</i>	2.86	54.38	5.13	<0.01	0.10
<i>Color × Technique</i>	2.27	43.06	0.35	0.73	<0.01
<i>Results for a*</i>					
<i>(Intercept)</i>	1.00	19.00	68.26	<0.01	0.61
<i>Color</i>	1.00	19.00	10.97	<0.01	0.06
<i>Technique</i>	4.00	76.00	15.11	<0.01	0.17
<i>Color × Technique</i>	4.00	76.00	1.97	0.11	0.02
<i>Results for b*</i>					
<i>(Intercept)</i>	1.00	19.00	55.84	<0.01	0.56
<i>Color</i>	1.00	19.00	0.09	0.77	<0.01
<i>Technique</i>	4.00	76.00	7.62	<0.01	0.09
<i>Color × Technique</i>	4.00	76.00	0.56	0.69	<0.01

Table 7.2: Results of the RM-ANOVAs of error scores in Exp. 2.

error scores. This pattern is evident for both colour axes. The differences in error scores compared to the baseline S_u appear in Table 7.3, where there are lower error rates for all techniques except GC_{bg} .

Effect sizes of other interactions are not large enough to be of practical relevance except for the interaction of colour and technique in the a^* axis, which is small but we decided to investigate nonetheless. A closer look revealed some outliers in the a^* -high condition. Otherwise both a^* -high as well as a^* -low show the same pattern (see Figure 7.6). The effect of colour in the a^* axis indicates that one of the gradients was more difficult than the other $M_D=1.8$, $d_{diff}=0.44$.

	S_f		GC_{patch}		$GC_{\text{bg+patch}}$		GC_{bg}	
	M_D	d_{diff}	M_D	d_{diff}	M_D	d_{diff}	M_D	d_{diff}
a*	-3.50	-1.04	-3.64	-1.05	-2.93	-0.61	-0.03	-0.01
b*	-1.92	-0.49	-1.50	-0.42	-2.15	-0.74	0.01	0.00

Table 7.3: Differences in error scores of each technique compared to the baseline technique S_u .

7.2 Discussion

The results from the colour sorting experiment show that gaze-contingent techniques that manipulate peripheral patches (GC_{patch} and $GC_{\text{bg+patch}}$) improve performance in a colour ordering task compared to the presentation on uniform background S_u , which is the baseline technique (H2.2 is supported). Surprisingly, gaze-contingent manipulation of only the background (i.e., only with SC) does not seem to help with colour differentiation as the GC_{bg} technique did not show a comparable advantage (H2.1 is *not* supported).

Therefore, it is likely that the advantages in the ordering task are due to peripheral colour patch manipulation. Although this is not strictly an SC effect, it is still a valid way to take advantage of gaze-contingency.

The static technique with the SC frames is interesting and deserves further investigation. As mentioned above, it is not feasible for full-range displays, but it might result in better colour differentiability for reduced ranges if it can be used, for example, by adding the colour to object outlines. This technique showed error scores comparable to the best GC-based techniques.

Even though in this instance the improvement for colour discrimination was not caused by the use of simultaneous contrast, it seems that gaze-contingent changes of peripheral objects can lead to a better colour discrimination ability. Perhaps a more targeted background adjustment (similar to the static individual background) that partially preserves relative background might lead to further improvements. However, this kind of technique will have to be investigated in future work.

The results suggest that the technique that was proposed by Cheng and Badano (2010) for presenting medical images have merit and can provide additional information to the observer. Also, the presented techniques could be applied to scenarios where colours need to be differentiated in a categorical way, for example, information visualisations that encode categories as colours.

Overall, this experiment provides evidence that gaze-contingent techniques can improve colour discrimination, thus demonstrating a clear benefit derived from low-level perceptual adjustments on GCDs for a task related to visual perception.

7.3 Conclusion

This chapter presented an empirical evaluation of gaze-contingent manipulation of colours through simultaneous contrast and peripheral object colour manipulation. It described an experiment that provides insight into the usefulness of these techniques to increase the ability of the observer to discriminate between colours on a gradient.

The results show that gaze-contingent manipulations are indeed able to reduce errors in a sorting task by manipulating the relative appearance of colours around the currently attended colour. The gaze-contingent local contrast enhancement could be used to increase the useful amount of information that a colour based information visualisations can convey.

IV

PART IV

APPLICATIONS & SOFTWARE

PYTHON COLOUR APPEARANCE MODELS

This chapter describes an additional outcome of this thesis: a software module that contains implementations of colour appearance models (CAMs). This module parallelized as part of the initial research on the background to Part III of this Thesis, and then made available to the public as part of an open source project. It serves to facilitate further research in the area of colour perception by providing easy access to historical models of colour perception, as well as standards that are currently in use in software systems. They will also play in important role in the further refinement of the techniques presented in Part III, as these will need further refinement based on the theoretical background provided by CAMs.

Colour appearance models (CAMs), as described in Section 2.5.3, are useful mathematical predictions of how colours are perceived given certain environmental factors, such as the global white point or influences of colour surround. However, to effectively use them, the pure mathematical formulations need to be available as software that can easily be used. While the literature (e.g., Fairchild 2013 or the primary papers cited therein) provides reference computations in Microsoft Excel, and other authors provide code examples, for example, in Matlab, so far

no comprehensive collection of CAMs existed. To solve this problem, I implemented the models described in Fairchild (2013) in a Python module. This code is now freely available under the MIT license as part of the colour-science library, created and maintained by Thomas Mansencal, as well as the python-color packages maintained by Greg Taylor. The following chapter will describe the implementation in the colour-science package.

Python is a high-level programming language that is commonly used for data processing and data analysis in scientific contexts. Python is easy to understand (Fangohr, 2010) and it widely used in the scientific community (Millman and Aivazis, 2011). While high level, it also has implementations of very efficient numeric data structures through the numpy libraries, allowing numerical computations to be executed very efficiently (Walt et al., 2011), alleviating one of the common drawbacks of high-level scripting languages. It, therefore, is a good choice to implement complex numerical models: they will be widely available, easily usable through high-level interfaces, but can be executed in an efficiently parallelized manner.

This chapter provides a general overview of the design and project. The code itself is available as part of the colour-science repository¹.

8.1 Project Aims

The aim of this module is to provide an easy to use, efficient implementation of the most common Colour Appearance Models. The module includes implementations of the CAMs described in Fairchild (2013):

- ATD95
- CIECAM02
- Hunt
- LLAB
- Nayatani95
- RLAB

¹<https://github.com/colour-science/colour>

8.2 Underlying Technology

The CAMs are implemented in Python and work with Python 2.7 and Python 3.X. They work with numeric values. The implementation is built on numpy, allowing flexibly shaped arrays as input and performs efficient parallelised computations.

8.3 Code Design

The models are implemented following a functional design, avoiding the use of classes and internal states. The code closely follows the mathematical description, to allow easy tracing of the steps that are performed in code and comparing them to the original formulation of the models from the source literature. This also allows proposed modifications of the mathematical formulations to be easily integrated since the corresponding sections can easily be identified.

The functions provide sensible defaults for most input parameters, where those are specified by the model authors. This allows them to generate sensible results for use cases where not all the input parameters are available.

The input parameters are grouped into compound objects where this makes sense, for example, CIECAM02 requires a group of related parameters “InductionFactors”, which are passed as part of a single parameter “CIECAM02_InductionFactors”, implemented as a named tuple. Since each model provides multiple predicted correlates, the return value of the model function is implemented in a similar way: the parameters are grouped in a return value object that provides access to each value through name. See Listing 8.1 for the example return object that is used for CIECAM02.

```
1 class CIECAM02_Specification(  
2     namedtuple('CIECAM02_Specification',  
3         ('J', 'C', 'h', 's', 'Q', 'M', 'H', 'HC'))):  
4     """  
5     Defines the CIECAM02 colour appearance model specification.  
6     Parameters  
7     -----  
8     J : numeric or array_like
```

```
9         Correlate of *Lightness* :math:`J`'.
10     C : numeric or array_like
11         Correlate of *chroma* :math:`C`'.
12     h : numeric or array_like
13         *Hue* angle :math:`h` in degrees.
14     s : numeric or array_like
15         Correlate of *saturation* :math:`s`'.
16     Q : numeric or array_like
17         Correlate of *brightness* :math:`Q`'.
18     M : numeric or array_like
19         Correlate of *colourfulness* :math:`M`'.
20     H : numeric or array_like
21         *Hue* :math:`h` quadrature :math:`H`'.
22     HC : numeric or array_like
23         *Hue* :math:`h` composition :math:`H^C`'.
24     """
```

Listing 8.1: Example return value specification for CIECAM02.

8.4 Code Validation

To ensure that the computations are correct, all the implemented CAMs come with unit test suites and the GitHub repository undergoes continuous integration testing. The implementations are tested against the example values given in Fairchild (2013), as well as the example computations given in the books supplementary material², which takes into account the latest errata (July 25, 2014).

8.5 Usage Example

This section will give two step by step examples that showcase the features of the CAM implementations. All examples are based on colour 0.3.7 running with Python 3.5.

8.5.1 Predicting Perceived Colour - Hunt Model

The Hunt model takes into account a large number of parameters and makes predictions based on many features of the visual system. Because of this, it is also fairly difficult to use. It requires input parameters that are not always available, for example, scotopic luminance data. This

²<http://rit-mcsl.org/fairchild/files/AppModEx.xls>

implementation allows for many of those parameters to be approximated through values that are easier to determine, although at the cost of accuracy. This example shows how predictions are computed with the minimal set of input parameters.

```
1 import numpy as np
2 from colour.appearance import HUNT_VIEWING_CONDITIONS, XYZ_to_Hunt
3
4 # CIE XYZ tristimulus values of test sample / stimulus in the domain
5   [0, 100].
6 XYZ = np.array([19.01, 20.00, 21.78])
7
8 # CIE XYZ tristimulus values of the reference white in the domain [0,
9   100].
10 XYZ_w = np.array([95.05, 100.00, 108.88])
11
12 # CIE XYZ tristimulus values of background in the domain [0, 100].
13 XYZ_b = np.array([95.05, 100.00, 108.88])
14
15 # Scotopic luminance of the illuminant.
16 L_A = 318.31
17
18 # Correlated color temperature of the illuminant,
19 CCT_w = 6504.0
20
21 # Compute the model predictions.
22 XYZ_to_Hunt(XYZ, XYZ_w, XYZ_b, L_A, CCT_w=CCT_w)
```

Listing 8.2: Example of how to compute Hunt model predictions.

8.5.2 Predicting Large Number of Colours - LLAB

Computing a large number of different colours through a CAM is very similar to just computing a single one. All that needs to be changed is that instead of a single array of XYZ values, a multi-dimensional array is passed to the function. The result values will have the same shape as the input array. The computation is performed on the provided arrays making use of the routines for efficient array manipulations that numpy provides.

```
1 import itertools
2 import numpy as np
3 from colour.appearance import XYZ_to_LLAB
4
```

8. PYTHON COLOUR APPEARANCE MODELS

```
5 # Create all possible integer valued XYZ coordinates in [0...100,
   # 0...100, 0...100].
6 XYZ = np.array(list(itertools.product(range(100), repeat=3)))
7
8 # Set up default environment / adaptation parameters.
9 # These could be multi-dimensional too if desired.
10 XYZ_0 = np.array([95.05, 100.00, 108.88])
11 Y_b = 20.0
12 L = 318.31
13
14 # Compute model predictions for all given colours.
15 XYZ_to_LLAB(XYZ, XYZ_0, Y_b, L)
```

Listing 8.3: Example of how to compute LLAB predictions for a large number of input colours.

8.6 Conclusion

The *colour.appearance* module provides a comprehensive tool-set for working with CAMs that is easy to use. It is available as part of the scientific computing ecosystem in Python, allowing it to be easily paired with tools for image processing and advanced statistical analysis. The efficient implementation through numpy arrays allows fast computations on large data-sets. The module makes it easier to work with CAMs without requiring the user to study the models in depth. It makes them accessible to a wider audience and provides sample procedures showcasing the internal workings of the models in an easy to understand high-level programming language. These models are of special interest for the further development of the techniques described in Part III, as they allow prediction of changes in colour perception based on surround and other environmental parameters.

CHAPTER NINE

GAZER — GAZE-CONTINGENT IMAGE VIEWER

This chapter describes Gazer, an application that features the gaze-contingent depth of field (GC DOF) rendering from Chapter 4 as well as colour based adjustment following the ideas from Chapter 6 and Chapter 7. Gazer is an additional outcome of this thesis that enables other researcher and the public to use gaze-contingent rendering with off-the-shelf hardware. Gazer provides functionality for rendering light field images using gaze-contingent focus and astronomical data with gaze-based contrast enhancement. It shows the practical benefits of GCDs, as well as providing an example of how they can be applied to existing problems.

So far there is very little end user software available that makes use of eye-tracking capabilities. Most of the software that is available consists of demos provided by the eye tracker manufacturer or is aimed at research and analytics. Example applications are emerging in the area of gaming. However, these are also mostly early stage prototypes or demos. So far there are no general purpose visualisation tools that make use of gaze-contingent capabilities.

To make it easy for others to use and extend Gazer, its codebase is available

under an open source license (GPL) and available through Github¹.

The following section is based on the current state of the development version of the software as of the writing of this thesis. Gazer is still under active development, and the up-to-date version might incorporate further improvements and extensions or differ in other ways from this description. The work on this application was supported by David Morrison who was contracted as a software developer to provide some of the back end functionality.

9.1 Aims of the Project

The main goal of Gazer is to enable the public to experience gaze-contingent rendering with cheap off-the-shelf hardware, as well as provide a starting point for other developers to create gaze-contingent visualisations. To achieve this Gazer is released as an open source application that is easily extensible. It comes with two modules that enable rendering of gaze-contingent DOF from Lytro light field data, and gaze-contingent colour rendering based on astronomical image data.

9.2 Underlying Technology

To facilitate rapid prototyping and easy extensions, the application is implemented in a high-level scripting language. Python is an ideal candidate for this. It has the capabilities to be multi-platform, the SDK for Lytro provides an API in Python and there are Python libraries that allow easy access to multiple Eye tracking APIs. Python also allows a convenient mix of high-level programming with access to high-performance computation through libraries that make use of OpenGL or C-based algorithms.

The user interface is implemented in PyQT, which is fast available for multiple platforms and freely available under the GPL license. It uses the Lytro Power Tools² for processing Lytro light field data, and Scipy (Jones et al., 2001), numpy (Walt et al., 2011), scikit-image (Van Der Walt et al.,

¹<https://github.com/MichaelMauderer/Gazer>

²<https://www.lytro.com/imaging/power-tools>

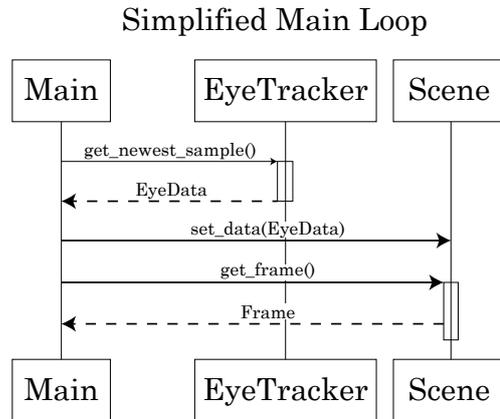


Figure 9.1: Simplified sequence diagram of Gazer’s main loop.

2014) and `astropy` (Astropy Collaboration et al., 2013) for image and data processing.

9.3 Code Design

Overall the implementation follows an object oriented approach which provides encapsulation and standardised interfaces for the varying sources of information and functionality required for the rendering loop. Different algorithms that render frames in response to the gaze position can easily be implemented and substituted. The rendering process itself is based on a simple rendering loop that is provided with data from the eye tracker to generate each frame from a *scene* object (see Figure 9.1). Scenes contain the actual rendering logic and can easily be exchanged to facilitate different algorithms, for example, to allow switching between applying DOF or colour changes.

9.3.1 .gc File Format

To enable the exchange of data for gaze-contingent scenes between users, for example via the web, Gazer provides a file format that facilitates the exchanging of scenes in a way that aims to be rendering algorithm agnostic and flexible. Each type of scene can use the format to encode its own data based on its requirements.

The file format uses a BSON (Binary JSON) wrapper as its base. BSON is an open format that can easily be read and written. It is a dictionary based format allowing division of metadata and payload. This way it is possible to define multiple ways to encode data into a common format.

```
{
  'encoder': 'gazer',
  'version': '0.1',
  'compression': 'none',
  'type': 'simple_array_stack',
  'data': <encoded scene data>
}
```

Listing 9.1: Example File Structure as JSON

The fields that are available allow flexible extension, fault tolerance as well as forward and backwards compatibility. 'encoder', 'version' both specify which application (and which version of it) produced the file, thus providing specific information about how the file was created. This allows the decoder to know exactly how to handle the file based on its source. 'compression' specifies whether the payload is compressed, and if so, which compression was used. This allows the file size to be kept small by providing a catch-all mechanism to reduce the payload size. 'type' specifies which kind of payload is encoded, allowing the application to chose the appropriate decoding algorithm and create the right scene object to display the data.

9.4 Current Functionality

Gazer supports the Tobii EyeX API³ for acquiring gaze data, as well as fallback functionality that allows the user to mock eye tracking information through common pointer input (mouse/touch) in case that no eye tracker is available.

Gazer provides modules for rendering GC DOF and astronomical data with local contrast enhancements. Both of these are further described in the following sections.

³<http://developer.tobii.com/>

9.4.1 GC DOF

Following on the results of the research on GCDOF presented in Chapter 4 as well as the related literature, the next natural step is to see which kind of data could best be served by its benefits. A good choice for this is light field data. Light field data is a photographic image data that has additional information that allows an image to be refocused (Georgiev et al., 2013). This already provides the right data that is required for GC DOF that can be used with the algorithm for GC DOF presentation described in Chapter 4. Light field cameras are available as an off-the-shelf consumer device (e.g., Lytro cameras) as well as research grade imaging equipment (e.g., Raytrix cameras). Since they are available to a wider audience, we chose to focus on images generated with Lytro cameras. See Figure 9.2 for an example of the Gazer DOF module presenting Lytro images.

While the content of the files is proprietary, Lytro has released an SDK that allows low-level access to the light field data. Gazer provides a converter that uses light field files to create a .gc file that can then be used for efficient rendering of GCDOF scenes.

9.4.1.1 GC DOF File format

The implementation for GC DOF data is based on ‘image stacks’ (see Figure 9.3). The data is stored as a depth map and frames with varying focus. The frames are stored so they can be matched to the depth from the depth map. By matching the correctly rendered image to each position in the depth map, Gazer can quickly show an image that is focused on the current gaze position.

9.4.1.2 Limitations

Currently, Gazer renders a single view of a 2D image with dynamic focus. Support for rendering binocular images on 3D displays could further enhance the impression of depth.

The file format for scenes incorporating GC DOF still produces relatively large files (>50MB) due to the large numbers of frames that get saved. Further specific compression, for example, based on difference frames,

9. GAZER — GAZE-CONTINGENT IMAGE VIEWER

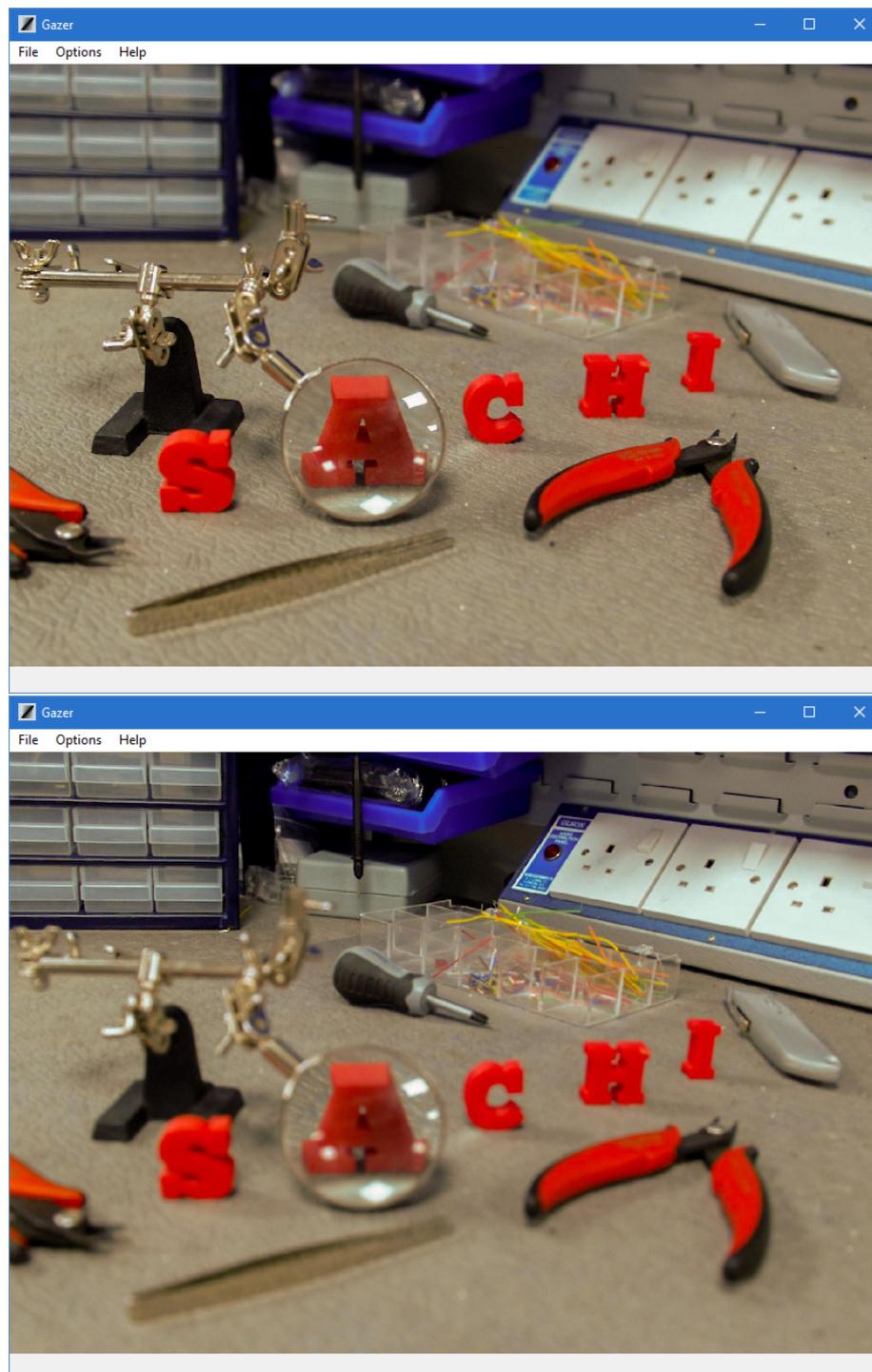


Figure 9.2: Images showing gazer displaying an photograph taken with the Lytro Illum. The left image shows the image focused at the 'A', the right images shows the focus at the background.

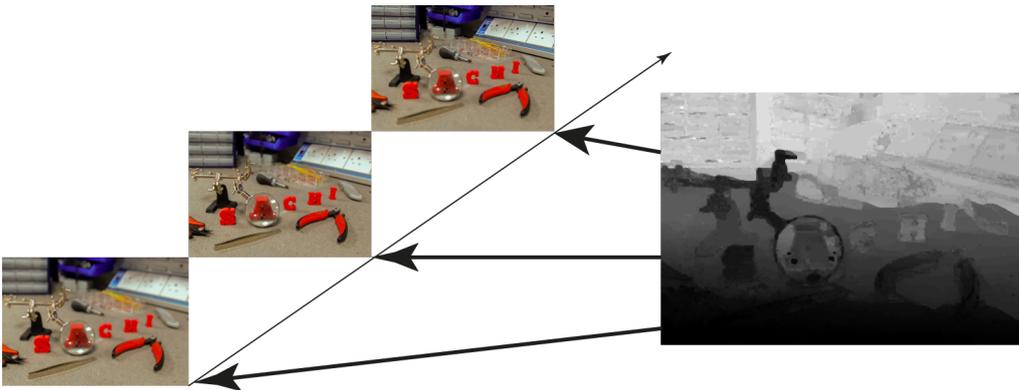


Figure 9.3: Illustration of the look-up process. A range of pre-focused images are stored and the image corresponding to the currently attended depth is selected and displayed.



Figure 9.4: Gazer rendering of a WISE (Wide-field Infrared Survey Explorer) observation data file. Once (left) while the Galaxy in the bottom left corner is attended and once (right) while the background is attended.

could lower the space requirement.

9.4.2 GC Colour

In addition to the GC DOF functionality, the application also supports colour based presentation of images in common file formats, as well as astronomical data in the *fits* data format. The rendering features for this data focuses on local contrast enhancement (see Figure 9.4 for an example).

9.4.3 Presentation Algorithm

The implementation of gaze-contingent colour adjustments is based on a histogram equalisation around the attended area. This allows small details to be visible at the cost of detail in non-attended areas (see Figure 9.4). The results from Chapter 7 have shown that contrast enhancement is a promising way to use gaze-contingent colour adjustments. Computing histogram equalisation is also fast, allowing real-time rendering of high-resolution images.

9.4.3.1 Limitations

The current implementation changes how colours are rendered. While it is based on image data it does not necessarily preserve all features of the original data (i.e., hue or relative brightness) in favour of increasing local contrast. Further improvements should take into account the intended appearance and aim to present the colours in a faithful way.

The current implementation transforms image colour using the colour-science package, which is based on numpy. While this provides fast CPU based computations, more complex transformations (e.g., to CIELAB and back to RGB) and larger images are still limited by the computational cost, making the process slow for fast rendering. Future development will have to move to a GPU/shader based model that can handle more complex computations on larger image data.

9.5 Conclusion

Gazer provides a novel way to view images. It allows perceiving light field images with dynamic focus, simulating the accommodation process of the eye while viewing photographic imagery. Gazer also facilitates the rendering of image data, allowing gaze-contingent contrast and colour enhancements, extending the amount of detail that can easily be perceived. Gazer translates the theoretical results from Part II and Part III into a working application. It provides an application that uses the basic research that was presented earlier in order to provide a more tangible outcome in addition to the theoretical results.



PART V

DISCUSSION &
CONCLUSION

10

CHAPTER TEN

DISCUSSION

This thesis set out to answer the overarching research question of whether “changing the peripheral display content around the current point of regard can be used to facilitate perception of the main content”. To answer this questions, it looked at two features of the attended content: depth and colour. To facilitate the perception of depth, peripheral depth of field (DOF) blur and chromatic aberration was rendered to simulate the focusing properties of the human eye. To facilitate the perception of colour, the peripheral colour was changed to use simultaneous contrast to create a larger visible gamut and increase local contrast.

This chapter summarises the high-level findings from the previous parts and presents a discussion about their wider implications, application areas as well as potential impact and future outlook of gaze-contingent (GC) technology in general.

10.1 Summary of Findings

In Part II and Part III this thesis presented four experiments that investigated gaze-contingent techniques that manipulated different aspects of visual perception. The experiments from Part II investigated effects related to depth perception, while the experiments from Part III were designed to investigate effects related to colour perception.

10.1.1 Findings on Depth Perception

The first experiment presented in Chapter 4 investigated how using peripheral blur based on a simulation of the eye's depth of field affects depth perception. It showed that GC DOF could provide additional information about depth and the separation of depth between objects, but the information content was limited.

The second experiment that investigates depth perception is presented in Chapter 5. It extends the previous GC DOF technique by adding an approximation of chromatic aberration, but it did not find an improvement in accuracy for depth estimation or ordering of objects over the basic method.

10.1.2 Findings on Colour Perception

The third experiment is described in Chapter 6 and investigates the basic properties of gaze-contingent colour manipulations based on simultaneous contrast for luminance and chromaticity. The results show that it is possible to use background manipulations to change the perception of an attended colour patch, potentially providing an extended perceived gamut.

The fourth and last experiment in Chapter 7 investigates different techniques to manipulate the colours on a display during a colour sorting task and found that local contrast enhancements can reduce the error rate, thus indicating that the colours were easier to differentiate.

10.2 Significance of Findings

This thesis set out to investigate whether it is possible to augment perception through peripheral gaze-contingent manipulations. Meaning, whether it is possible to use basic properties of the displayed content to provide a benefit to the observer without changing the content itself, but only the unattended areas around it. Thus, allowing for manipulations that should be unobtrusive to the observer. The findings show that in summary the answer to the question whether it is possible is a *Yes*. These

results have significance for perceptual psychology, computer graphics and the field of gaze-contingent displays in general.

10.2.1 Supporting Depth Perception

The results from Part II suggest that modifying the texture of the area around the point an observer is looking at to simulate DOF can be useful as a depth cue. While the benefits of GC DOF for depth perception are small on its own, it could complement other existing ways of providing 3D such as binocular disparity. Even a small benefit for depth perception makes it useful, especially as it has other benefits for realism (Mauderer et al., 2014), and visual fatigue (Duchowski et al., 2014). More so, it is feasible that it could be used in more exaggerated ways, similar to the example in Figure 2.10 to change the impression of the size of the whole scene and affect the perception of size in virtual environments.

While GC DOF could be used in every 3D display, it is of special interest in VR headsets, where the impression of realism and visual fatigue are highly important and simulator sickness is a common problem. Headsets are also designed as personal displays, avoiding the problems of multiple observers. Only a single gaze point has to be taken into account. The addition of DOF could also help mixed reality headsets to better integrate virtual objects into the real scene by modifying their blur to be consistent with the real world objects, avoiding the jarring contrast otherwise created (Kán and Kaufmann, 2012).

Dynamic DOF is also used in different ways. Movies as well as computer games, for example, make use of DOF to guide the viewer's attention or keep it in specific areas of the scene (Katz, 1991). This means that even without a GCD the DOF can enhance the observer's sense of realism and depth. In these cases, however, care is taken during scene transitions or cuts that the viewer never directly is looking at a blurred area. Camera movement and focus are directed in a way to create smooth transitions the viewer can follow without noticing. However, it is feasible to use a mixed approach of directed DOF and GC DOF in movies, games or similar media. The DOF could, in general, follow the viewers gaze, facilitating immersion and realism. During specific scenes it could then be decoupled from the observer's gaze and instead be used to guide the viewer's attention,

subtly drawing the gaze to specific events on screen. This combination could create a new technique for storytelling, in which the viewer has a high degree of immersion, but the director still can control the viewer's attention when required.

GC DOF could also be used a new research method in perceptual research. The findings have been consistent with previous investigations of DOF that have made use of other methods, for example, static images. This shows that GC DOF is a comparable valid way to research perception related to DOF in the human visual system. Because controlling the DOF of the eye itself is very difficult, previous research used static images that incorporate varying degrees of blur. Rendering GC DOF could provide a new means to present DOF in a way that is potentially more faithful to real-world viewing conditions. It allows the focus in a scene can change arbitrarily depending on where someone would look, instead of presenting a fixed focus and requiring a specific point to be observed. Manipulations of how the GC DOF is presented and how someone would react to these manipulations could thus give insight into how the visual system processes the information provided by the eye's DOF. GC DOF could, therefore, be a useful new method for exploring how DOF is incorporated as a depth cue in the human visual system, and it could lead to new lines of research that provide novel insights into how humans perceive depth.

10.2.2 Supporting Colour Perception

The results from Part III suggest that modifying the colour of the area around the point an observer is looking at in a gaze-contingent way, can be used to modify how the colour is perceived, potentially increasing the perceivable colour gamut and it can be used to make colours more differentiable. This opens a new avenue of using GCDs: as a dynamic range extension of existing displays. Current display technology has reached a point where the resolution is no longer the main limiting factor as the pixel density matches and exceed the resolution of the retina at standard viewing distances. Companies are starting to look at other areas of improvement, namely higher dynamic range (HDR). GCDs could be used on top of any advances in display technology to boost further the

dynamic range an observer could perceive on a given display, simply by the addition of eye tracking.

Higher dynamic ranges are not only growing in importance in the entertainment industry. Other displays have comparably limited capabilities: mixed virtual reality displays. For example, the displays in Microsoft's Holo Lenses currently requires the view of the real world to be dimmed down behind a tinted screen to match the brightness of the real world to the display's brightness. These displays could greatly benefit from technology that increases the available dynamic range or increases the local contrast of the content that is shown. As these are personal displays located on the head, they are perfectly suited for the addition of eye tracking and in fact either already provide some of its functionality, or can be augmented with eye tracking kits, for example, provided by SMI¹.

The restrictions of dynamic range are not only a concern for displays trying to show images of the real world. Astronomy deals with data that is generated from spectra that are far beyond what the human eye can see. However, still visual inspection of this data can be of great benefit to detect interesting patterns (Jarrett et al., 2012). But neither can this data be rendered in its original form, nor is a simple transformation possible that could preserve all the detail contained in the rich original data. Gaze-contingent adaptations of these spectral images could allow astronomers a new view of the data they collect and thus generate new insights.

A similar argument can be made for medical data generated from x-rays and indeed has been made by Cheng and Badano (2010). However, going beyond monochrome data sources, there are other medical imaging techniques, for example, MRIs, which provide much denser and multi-dimensional data, requiring the use of additional colour dimensions to convey their complete content. Extending the dynamic range and contrast in these dimensions through GCD techniques could have a big impact in how well these images can be analysed by practitioners.

On a more general level, having a higher dynamic range is of course not only useful for images, but any data. Information visualisation principles tell us, that in general there are a limited number of hues

¹<http://www.smivision.com/en/gaze-and-eye-tracking-systems/products/eye-tracking-hmd-upgrade.html>

that can be differentiated (Bertin, 1983). However, using GCD techniques we can push this number, strengthening the power of visual inspection. Specific techniques could be developed that consider the semantics of the presented information when considering how to recolour the surround, to create new ways to convey this information, for example, by pairing specific colours to indicate categories.

Since the changes that re-induced by a GCD are specific to the individual observer, they can also easily consider the abilities of the individual. The ability to differentiate specific colours can vary from person to person, with the extreme example of red-/green colour blindness. So not only could colour based GCDs increase the dynamic range in general, they could be used to allow individuals to increase their personal colour differentiation ability by making colours especially distinct when they are hard to differentiate for this person.

10.3 Gaze-contingent Displays revisited

Eye tracking and as an extension gaze-contingent displays are useful as tools to research perception and a means of rendering while taking into account the current perception and cognition of the observer. This thesis presents findings from the area of depth and colour perception. However, the implications reach further than these two fields. The results show that gaze-contingent displays can be useful in a new way: supporting the users' perception on a fundamental level. By facilitating low-level processes of perception, this kind of technique has the potential to impact all stages of the visual system, as well the cognition that is processing the visual stimuli. Looking at gaze-contingent displays as a means of supporting perception adds a new perspective on the impact that wide availability of eye tracking could have, beyond the current mainstream applications.

Gaze-contingent methods in research allow researchers to probe the visual system by changing stimuli in reaction to peoples' gaze. From observing peoples' response to manipulations of the content that they are observing, a direct mapping between the input to the visual system and its reaction can be established. The data from this kind of investigation

allows the creation of detailed models based on the input-output measures of the visual system. The insights are not limited to low-level perception but can also include higher cognition, like reading or object recognition, depending on the features that are manipulated, like for example, text. These insights are only possible because GCDs allow the very precise manipulate of the input to the visual system.

Gaze-contingent multi-resolution rendering also makes use of the precise nature of presentation that GCDs enable. They build on the knowledge about human vision and exploit the fact that the observer can not detect specific things on a display, for example, the high-resolution detail in the periphery of the visual field. Leaving out these details can have a drastic effect on the rendering effort it takes to create an image without affecting the observers' experience. By rendering exactly to the ability of the visual system, GCDs free up resources that can be used to render the parts of the image that are perceived more realistic and with a higher framerate. Gaze-contingent multi-resolution rendering is an enabling technology for VR/AR headsets, which need to be low in power consumption since they run on battery but also require a high degree of realism to facilitate immersion.

Gaze-based detection and direction of attention allows systems to infer valuable information about the cognition of the observer and influence the observer's cognition. It can determine the content that the observer perceives and can change how an observer thinks about the presented content. Also, the system can create a mental model of the observer, that contains information about what the observer knows, and from there can change its content to fit the needs and aims of the observer. For example, it can keep track of what the observer has already read and understood the content and then present additional information accordingly. Since all of this can be done without the observer noticing, it is a powerful way to convey information that can make sure that the observer is aware of specific information or even guiding them through trains of thoughts by drawing their attention to specific information in a specific order.

Gaze-contingent perceptual augmentation takes the knowledge about the observers' visual perception and tries to optimise the presentation of content. This can be used to facilitate perception and make it easier to

solve a task, to make the content easier accessible, or to convey additional information that would otherwise be inaccessible. The basic approach for this is to take the models of human perception and find a way to optimise the input to the visual system so it can be processed in an optimal way. This can mean that the systems exploit low-level processes by providing specific stimuli from which we know that they are interpreted in a specific way, for example, simultaneous contrast. The benefit of targeting low-level features, is that we can find techniques that apply to a large range of content, for instance, colour applies to virtually everything that is displayed. Thus, being able to enhance how specific aspects of colour are perceived could impact every kind of content. However, we could also look at other higher level features of vision like movement, or even object recognition and change how we present content, for example, to make sure the movement is detected when needed or specific objects are recognised as intended.

The two unifying factors of the approaches described above are that they require the detailed knowledge of human perception and precise control over how the content is presented. The knowledge about the visual systems allows us to devise techniques and predict their effects. The eye-tracking component allows us to specifically manipulate the display content, mostly based on where in the retina it will be perceived. That is, whether the display content will be processed in the fovea or in the periphery of the retina. Controlling the content and predicting how it is perceived allows us to save bandwidth, learn about the human visual systems, and now even optimise the presentation to facilitate the perception of the content. The later which enables us to create entirely new ways to present content.

With more and more precise control over the content, we might not only be able to distinguish between central and peripheral presentation but determine the exact location of the retina content will be projected to. With this kind of precision, we might not only be able to facilitate perception of existing naturalistic content. We might be able to create new sensations, which do not appear in natural viewing. For example, by creating new input channels altogether: we could re-purpose areas in the retina to render specific contextual colours that are not part of the

currently attended scene but convey contextual information, for example, the temperature of the scene environment. This additional information could be picked up by the visual system and be re-interpreted in later stages of cognition. There is evidence that the visual system has the plasticity to re-interpret its input to a large extent going so far as to adapting to a complete inversion of the visual field through special goggles (Kohler, 1963) and after some time re-interpreting the input and perceiving the world as upright again. This kind of manipulation would require a very high precision of content presentation and a long exposure for the brain to adapt to it. However, this is in some part, just what GCDs are trying to achieve. Even so, it might be that GCDs in this regard are just a stepping stone for other rendering techniques that do not use today's displays but render directly onto the retina. Those displays will benefit from the insights that are gained from designing gaze-contingent manipulations as the same basic techniques will be applicable there.

10.4 Directions for Research and Open Challenges

Challenges

While eye tracking is not ubiquitous yet, cameras laptops, tablets and phones might soon be able to provide eye tracking capabilities to a large number of devices. This thesis has shown, that it is possible to use the eye tracking to create GCDs that can boost the capabilities of the display on basic levels that can be useful in many applications. However, the presented GCD techniques require a high degree of precision. They need to change the display content very fast in response to the eye movements, they require accurate information about the observer's gaze, and they require a high degree of knowledge about the visual system and potentially about the environmental conditions around the display. This could result in systems that can be difficult to implement and hard to deploy in the wild. However, as Chapter 9 has shown it is after all possible to develop the research prototype techniques into end-user applications using off-the-shelf hardware.

In general, the utility of GCDs is limited to one observer per display as, in general, neither the rendering nor the eye tracking supports multiple

people. However, it is not unfeasible that eye tracking will be able to track the gaze of multiple people, and displays could be able to render multiple views, which already happens in displays that provide binocular 3D. More so, personal displays that are used by only a single observer are becoming more and more common: phones, smartwatches and head-mounted VR sets are intended to be used by a single person only. Thus they are ideal candidates to be converted into GCDs by the addition of eye tracking.

GCDs could also make use of other output modalities, even though a different name than “display” might be more applicable for such systems. For example, instead of just changing the visual content, the system could react with auditory cues, haptic feedback or other even olfactory changes in the environment. Even in the area of visual manipulations, there are other aspects besides depth and colour perception that can still be explored, for example, the perception of motion and form could be manipulated.

The direction that GCDs, and especially GCDs that focus in interacting with visual perception are going is clearly a promising one. If technology were not an issue, the perfect GCD would be able to project an image into specific areas of the retina with high precision. This would allow stimulation of specific regions of the eye, giving us full control over the visual signal that is sent to the brain. With enough knowledge on how this signal is interpreted, we could create completely new visual impressions, maybe even by targeting specific rod and cone areas in individuals. Of course, current technology is far from this, but it is the current research that lays the foundation for future techniques that could one day be used this way.

CONCLUSION

Gaze-contingent displays (GCDs) can infer information about the current perception of the user through their eye tracking capability and thus hold the promise of image rendering that can consider the details of our visual perception. This thesis set out to explore how GCDs can be used to go beyond the current capabilities of display technology to support people's perception, for example, for more realistic rendering or better performance in tasks that are related to depth or colour perception.

At first, this thesis looked at the area of gaze-contingent depth of field which Rahardja et al. (2009) has identified as a depth cue that could facilitate a more comprehensive representation of 3D content. While some researchers have already deployed it in virtual environments, they did not yet establish any clear empirical evidence for benefits relating to depth perception and distance judgement. The first experiment provided this empirical data and quantified the benefit of rendering gaze-contingent depth of field (GC DOF), showing that it presents an advantage for separating objects in depth, but it does not contain reliable information about the ordering of objects.

In a next step, this thesis investigated an approach to expand the usefulness of GC DOF by rendering it in a more optically faithful way, adding the properties of chromatic aberration with the intent of solving problems that GC DOF had with sign ambiguity. However, there was no clear improvement for depth judgements over the simplified DOF rendering, which suggests that chromatic aberration is not a strong depth cue, or

11. CONCLUSION

an even more optically faithful rendering process is required to make it work.

To show a wider range of applications for GCDs beyond what had the literature has previously proposed this thesis investigated manipulations of colour perception. It explored how GCDs can affect the perception of colour through dynamic simultaneous contrast and facilitate colour discrimination. It established that gaze-contingent simultaneous contrast can influence the perception of colour, potentially extending the perceived display gamut allowing more colours to be displayed on existing hardware, as well aiding in colour differentiation during a colour sorting task through manipulation of peripheral objects.

In addition to the empirical investigations this thesis also comes with two software packages that researchers to extend the presented work and demonstrates its benefits. One is a Python module that makes existing models of colour perception available through the Python colour-science package. The other, an application 'Gazer' demonstrates the effects of gaze-contingent DOF and colour manipulations, as well as enabling other developers to create their own gaze-contingent techniques.

The main contributions of this thesis are the results of the empirical investigations of gaze-contingent techniques. The first two techniques aim at improving depth discrimination and distance judgement. The second two techniques affect the perception of colour with the goal of extending the perceived colour gamut of displays and facilitate colour discrimination. All of these techniques promote the idea of facilitating visual perception and show that we can use GCDs to support the observer.

The main results are

- Evidence that depth perception can be augmented with gaze-contingent depth of field (GC DOF)
- Evidence, that manipulation of peripheral colour, can be used to affect the attended colour through simultaneous contrast
- Evidence that the manipulation of peripheral colours can be used to make different colours in a display easier differentiable.

All of these results support the thesis statement and show that peripheral changes of the display can be used to facilitate the perception of main content.

11.1 Future Research

The presented investigations show that gaze-contingent manipulation of perception is feasible and promising but also hard to get right. Future research in this area is required to optimise the techniques that have been presented and explore new avenues of perceptual manipulations beyond colour and depth perception.

F1: Integrating depth of field with other depth cues

The presented research has specifically focused on isolating DOF from other depth cues to get an accurate representation of its usefulness. However, in real world applications DOF will appear together with other pictorial depth cues and even binocular disparity in a 3D or VR environment. The use of DOF in this context does not even have to rely on eye tracking, but could also be achieved, for example, through light field displays. The results from this line of research could be display technology that can facilitate a complete natural viewing experience that is indistinguishable from a real scene.

F2: Find ways to integrate gaze-contingent colour into colour management systems

To make the best use and achieve the highest impact operating systems could incorporate gaze-contingent manipulations in their colour management systems. Colour management systems ensure that the display shows the correct colour, as intended by the software. These modules already make use of colour appearance modules like CIECAM02 to take into account environmental factors. If eye tracking is available, they could make use of gaze-contingent changes to achieve a more faithful colour reproduction and extend the perceivable display gamut. By integrating this functionality on an operating system level, existing applications do not have to change their behaviour to benefit from the improved colour reproduction. To achieve this goal, the presented techniques need to be

11. CONCLUSION

refined to work reliably in various contexts and eye tracking data needs to be available on an operating system.

F3: Develop robust gaze-contingent displays

For a broad audience to adopt GCDs, they need to be cheap and easy to use. Since cheap eye-tracking hardware has limitations regarding latency and accuracy, the first generation of GCD techniques needs to be robust to inaccuracy and delays. It is, therefore, important to investigate the requirements of techniques and the limits of the available hardware to create techniques that can be deployed to end users.

F4: Improved eye tracking

The flip side of the demand for robust GCD techniques is the demand for fast, accurate and easy to use eye tracking. If GCDs are ever to be useful to the end user, eye tracking needs to be as naturally integrated into end-user systems as keyboard and mouse. They need to provide reliable data in various environments and ideally, do away with time-consuming calibration procedures.

F5: Designing multi-modal gaze-contingent displays

This thesis focuses on gaze-contingent techniques that use the gaze information for its visual content. However, visual content is often accompanied by other modalities like sound, or even tactile feedback. These modalities could be linked and more complex gaze-contingent systems that support a variety of senses through multi-modal feedback.

11.2 Closing Remarks

Gaze-contingent perceptual augmentations hold great promise. They can enrich displays and support the users' perception. This thesis contributes to the basic understanding of how we can employ GCDs for enriching 3D content, supporting depth perception, augmenting the colour rendering capabilities of displays and increasing the colour differentiation ability of people. This thesis has shown this through basic experimental research, and it provides the tools for everyone to try this for themselves through

open source applications. These insights and tools can inspire and facilitate the development of new presentation techniques based on eye tracking information.

REFERENCES

- Aguilar, C. and Castet, E. (2011). Gaze-contingent simulation of retinopathy: some potential pitfalls and remedies. *Vision research*, 51(9):997–1012.
- Ashmore, M., Duchowski, A. T., and Shoemaker, G. (2005). Efficient Eye Pointing with a Fisheye Lens. In *Proceedings of Graphics Interface*, pages 203–210.
- ASTARResearch (2011). Demonstration of the EyeHDR technology.
- Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., Greenfield, P., Droettboom, M., Bray, E., Aldcroft, T., Davis, M., Ginsburg, A., Price-Whelan, A. M., Kerzendorf, W. E., Conley, A., Crighton, N., Barbary, K., Muna, D., Ferguson, H., Grollier, F., Parikh, M. M., Nair, P. H., Unther, H. M., Deil, C., Woillez, J., Conseil, S., Kramer, R., Turner, J. E. H., Singer, L., Fox, R., Weaver, B. A., Zabalza, V., Edwards, Z. I., Azalee Bostroem, K., Burke, D. J., Casey, A. R., Crawford, S. M., Dencheva, N., Ely, J., Jenness, T., Labrie, K., Lim, P. L., Pierfederici, F., Pontzen, A., Ptak, A., Refsdal, B., Servillat, M., and Streicher, O. (2013). Astropy: A community Python package for astronomy. *Astronomy & Astrophysics*, 558:A33.
- Atchison, D. A. and Smith, G. (2005). Chromatic dispersions of the ocular media of human eyes. *Journal of the Optical Society of America A*, 22(1):29–37.
- Bailey, R., McNamara, A., Costello, A., Sridharan, S., and Grimm, C. (2012). Impact of subtle gaze direction on short-term spatial information recall. In *Proceedings of the Symposium on Eye Tracking Research and Applications - ETRA '12*, volume 1, pages 67–74, New York, New York, USA. ACM Press.

REFERENCES

- Bailey, R., McNamara, A., Sudarsanam, N., and Grimm, C. (2009). Subtle gaze direction. *ACM Transactions on Graphics*, 28(4):1–14.
- Barth, E., Dorr, M., Böhme, M., Gegenfurtner, K., and Martinetz, T. (2006). Guiding the mind’s eye: improving communication and vision by external control of the scanpath. In Rogowitz, B. E., Pappas, T. N., and Daly, S. J., editors, *Electronic Imaging 2006*, volume 6057, pages 60570D–60570D–8. International Society for Optics and Photonics.
- Bartz, D., Cunningham, D., Fischer, J., and Wallraven, C. (2008). The Role of Perception for Computer Graphics. *Eurographics state-of-the-art-reports*, pages 65–86.
- Baudisch, P., DeCarlo, D., Duchowski, A. T., and Geisler, W. S. (2003). Focusing on the essential: considering attention in display design. *Communications of the ACM*, 46(3):60–66.
- Bertin, J. (1983). *Semiology of graphics: diagrams, networks, maps*.
- Blackwell, K. T. and Buchsbaum, G. (1988). The effect of spatial and chromatic parameters on chromatic induction. *Color Research & Application*, 13(3):166–173.
- Blakeslee, B. and McCourt, M. E. (1999). A multiscale spatial filtering account of the White effect, simultaneous brightness contrast and grating induction. *Vision research*, 39(26):4361–4377.
- Brooker, J. P. and Sharkey, P. M. (2001). Operator performance evaluation of controlled depth of field in a stereographically displayed virtual environment. In *Proc of Electronic Imaging*, volume 4297, pages 408–417. SPIE.
- Campbell, B. Y. F. W., Gubisch, R. W., Kruger, P. B., Mathews, S., Aggarwala, K. R., Sanchez, N., Mantiuk, R., Bazyluk, B., Tomaszewska, A., Eroglu S., Toprak S., U. O. M. O. E. O. M. A. D. M. H. A. M. C. O. M. E. A. M., Duchowski, A. T., House, D. H., Gestring, J., Wang, R. I., Krejtz, K., Krejtz, I., Mantiuk, R., Bazyluk, B., Stromeyer, C., Zhang, X., Thibos, L. N., Bradley, A., Williams, D. R., Sekiguchi, N., Haake, W., Brainard, D., Packer, O., Kruger, P. B., Mathews, S., Aggarwala, K. R., Yager, D., Kruger, E. S., Rucker, F. J., Kruger, P. B., Stark, L. R., Lee,

- R. S., Kruger, P. B., Rucker, F. J., Ying Fan, H., Kruger, P. B., Rucker, F. J., Hu, C., Rutman, H., Schmidt, N. W., Roditis, V., Lee, J. H., Stark, L. R., Cohen, S., Kruger, P. B., Sa'alam, M., Glasauer, S., Lehnen, N., Hillaire, S., Lecuyer, A., Cozot, R., Casiez, G., Gross, H., Blechinger, F., Achtner, B., Singer, W., Allison, R. S., Howard, I. P., Zacher, J. E., Thibos, L. N., Ye, M., Zhang, X., Bradley, A., Bennett, A., Rabbetts, R., Carlile, S., Jin, C., Harvey, V., Packer, O., Williams, D. R., Mutti, D. O., Roorda, A., Carlile, S., Leong, P., Hyams, S., Feldmann, H., Jones, S., Klenk, H.-D., Schnittler, H.-J., MacKenzie, K. J., Hoffman, D. M., Watt, S. J., and Roorda, A. (1999). Human Eye. *Vision Research*, 33(3):223–235.
- Charman, W. N. and Tucker, J. (1978). Accommodation and color. *Journal of the Optical Society of America*, 68(4):459–71.
- Cheng, W.-C. C. and Badano, A. (2010). A gaze-contingent high-dynamic range display for medical imaging applications. *SPIE Medical Imaging*, 7627:76270A–76270A–6.
- Chiu, K., Herf, M., Shirley, P., Swamy, S., Wang, C., Zimmerman, K., and Others (1993). Spatially nonuniform scaling functions for high contrast images. In *Graphics Interface*, page 245.
- Collewijn, H. and Kowler, E. (2008). The significance of microsaccades for vision and oculomotor control. *Journal of Vision*, 8(14):20.
- Cook, R. L., Porter, T., and Carpenter, L. (1984). Distributed ray tracing. In *ACM SIGGRAPH Computer Graphics*, volume 18, pages 137–145. ACM.
- Cornelissen, F. W., Bruin, K. J., and Kooijman, A. C. (2005). The influence of artificial scotomas on eye movements during visual search. *Optometry & Vision Science*, 82(1):1–10.
- Cumming, G. (2013). *Understanding the new statistics: Effect sizes, confidence intervals, and meta-analysis*. Routledge.
- Cumming, G. and Friend, H. (1980). Perception at the blind spot and tilt aftereffect. *Perception*, 9(2):233–238.
- Curcio, C. A., Sloan, K. R., Packer, O., Hendrickson, A. E., and Kalina, R. E. (1987). Distribution of cones in human and monkey retina: individual variability and radial asymmetry. *Science*, 236(4801):579–582.

REFERENCES

- Cutting, J. E. and Vishton, P. M. (1995). Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth. In *Perception of Space and Motion*, chapter 3, pages 69–117. Academic Press.
- Dalrymple, K. a., Bischof, W. F., Cameron, D., Barton, J. J. S., and Kingstone, A. (2010). Simulating simultanagnosia: spatially constricted vision mimics local capture and the global processing deficit. *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale*, 202(2):445–55.
- Danforth, R., Duchowski, A., Geist, R., and Mcaliley, E. (2000). A Platform for Gaze-Contingent Virtual Environments. *Smart Graphics (Papers from the 2000 AAAI Spring Symposium, Technical Report SS-00-04)*, pages 66–70.
- Dirik, A. E., Bayram, S., Senear, H. T., Memon, N., Sencar, H. T., and Memon, N. (2006). New Features to Identify Computer Generated Images. In *Proceedings - International Conference on Image Processing, ICIP*, volume 4, pages 433–436.
- Duchowski, A. and Eaddy, T. (2009). A gaze-contingent display compensating for scotomata. *Eurographics*, page 2009.
- Duchowski, A. T. (2002). A breadth-first survey of eye-tracking applications. *Behavior research methods, instruments, & computers : a journal of the Psychonomic Society, Inc*, 34(4):455–70.
- Duchowski, A. T., Bate, D., Stringfellow, P., Thakur, K., Melloy, B. J., and Gramopadhye, A. K. (2009). On spatiochromatic visual sensitivity and peripheral color LOD management. *ACM Transactions on Applied Perception*, 6(2):1–18.
- Duchowski, A. T., Cournia, N., and Murphy, H. (2004). Gaze-contingent displays: a review. *Cyberpsychology & behavior : the impact of the Internet, multimedia and virtual reality on behavior and society*, 7(6):621–34.
- Duchowski, A. T., House, D. H., Gestring, J., Wang, R. I., Krejtz, K., Krejtz, I., Mantiuk, R., and Bazyluk, B. (2014). Reducing visual discomfort of 3d stereoscopic displays with gaze-contingent depth-of-field. In *Proceedings of the ACM Symposium on Applied Perception*, pages 39–46. ACM.

- Duchowski, A. T. and McCormick, B. H. (1995). Preattentive considerations for gaze-contingent image processing. In *IS&T/SPIE's Symposium on Electronic Imaging: Science & Technology*, volume 2411, pages 128–139. International Society for Optics and Photonics.
- Fairchild, M. D. (2013). *Color Appearance Models*. The Wiley-IS&T Series in Imaging Science and Technology. Wiley, 3 edition.
- Fairchild, M. D. and Reniff, L. (1995). Time-course of chromatic adaptation for color-appearance judgments. *Journal of the Optical Society of America a-Optics Image Science and Vision*, 12(5):824–833.
- Fangohr, H. (2010). A comparison of C, Matlab and Python as teaching languages in engineering. In *Lecture Notes in Computer Science*, volume 3039, pages 1210–1217. Springer.
- Farhadi-Niaki, F. (2010). A Review on Eye-Gaze Tracking, GCDs, and Implemented Foveated Imaging Systems Using Optimized Methods. *Computers in Human Behavior*.
- Farnsworth, D. (1943). The Farnsworth-Munsell 100-Hue and Dichotomous Tests for Color Vision. *Journal of the Optical Society of America*, 33(10):568.
- Faul, F., Erdfelder, E., Lang, A.-G., and Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior research methods*, 39(2):175–191.
- Field, A. (2013). *Discovering statistics using IBM SPSS statistics*. Sage.
- Flatla, D. D. R. and Gutwin, C. (2010). Individual models of color differentiation to improve interpretability of information visualization. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2563–2572.
- Fortenbaugh, F. C., Hicks, J. C., Hao, L., and Turano, K. a. (2007). A technique for simulating visual field losses in virtual environments to study human navigation. *Behavior research methods*, 39(3):552–60.
- Fry, G. A. and Somers, W. W. (1974). Effect of blur and overlap on brightness matching. *Journal of the Optical Society of America*, 64(5):717–725.

REFERENCES

- Garcia, J., Sanchez, J., Orriols, X., and Binefa, X. (2000). Chromatic aberration and depth extraction. *Proceedings 15th International Conference on Pattern Recognition. ICPR-2000*, 1:762–765.
- Geisler, W. S., Perry, J. S., and Najemnik, J. (2006). Visual search: the role of peripheral information measured using gaze-contingent displays. *Journal of vision*, 6(9):858–73.
- Georgiev, T., Yu, Z., Lumsdaine, A., and Goma, S. (2013). Lytro camera technology: theory, algorithms, performance analysis. In Snoek, C. G. M., Kennedy, L. S., Creutzburg, R., Akopian, D., Wüller, D., Matherson, K. J., Georgiev, T. G., and Lumsdaine, A., editors, *IS&T/SPIE Electronic Imaging*, volume 8667, page 86671J. SPIE.
- Goldstein, E. B. (2013). Sensation and perception.
- Hartridge, H. (1918). Chromatic aberration and resolving power of the eye. *The Journal of physiology*, 52(4):175–246.
- Held, R. T., Cooper, E. a., and Banks, M. S. (2012). Blur and disparity are complementary cues to depth. *Current Biology*, 22(5):426–31.
- Held, R. T., Cooper, E. A., Banks, M. S., and O'Brien, J. F. (2010). Using Blur to Affect Perceived Distance and Size. In *Transactions on Graphics*, page 19. ACM.
- Henson, R. K. (2006). Beyond Significance Testing : Reforming Data Analysis Methods in Behavioral Research.
- Hillaire, S., Lécuyer, A., Cozot, R., and Casiez, G. (2008). Using an eye-tracking system to improve camera motions and depth-of-field blur effects in virtual environments. In *Proceedings - IEEE Virtual Reality*, pages 47–50. IEEE.
- Howarth, P. A., Zhang, X. X., Bradley, A., Still, D. L., and Thibos, L. N. (1988). Does the chromatic aberration of the eye vary with age? *Journal of the Optical Society of America A*, 5(12):2087–2092.
- Hunt, R. W. G. (1952). Light and Dark Adaptation and the Perception of Color. *Journal of the Optical Society of America*, 42(3):190–199.

- Hunt, R. W. G. (1987). A model of colour vision for predicting colour appearance in various viewing conditions. *Color Research & Application*, 12(6):297–314.
- Hunt, R. W. G. (1994). An improved predictor of colourfulness in a model of colour vision. *Color Research and Application*, 19(1):23 – 26.
- Jacobs, D. E., Gallo, O., A. Cooper, E., Pulli, K., and Levoy, M. (2015). Simulating the Visual Experience of Very Bright and Very Dark Scenes. *ACM Transactions on Graphics*, 34(3):25:1–25:15.
- Jameson, D. and Hurvich, L. M. (1961). Opponent chromatic induction: experimental evaluation and theoretical account. *Journal of the Optical Society of America*, 51(1):46–53.
- Jarrett, T. H., Masci, F., Tsai, C. W., Petty, S., Cluver, M. E., Assef, R. J., Benford, D., Blain, A., Bridge, C., Donoso, E., and others (2012). Extending the Nearby Galaxy Heritage with WISE: First Results from the WISE Enhanced Resolution Galaxy Atlas. *The Astronomical Journal*, 145(1):6.
- Jobson, D. J., Rahman, Z.-u., and Woodell, G. A. (1996). Retinex image processing: Improved fidelity to direct visual observation. In *Color and Imaging Conference*, number 1, pages 124–125. Society for Imaging Science and Technology.
- Jones, E., Oliphant, T., Peterson, P., and others (2001). {SciPy}: Open source scientific tools for {Python}.
- Jones, M. G., Nikolov, S. G., Newman, T. D., Bull, D. R., and Canagarajah, N. C. (2004). Gaze-Contingent Display Using Texture Mapping and OpenGL : System and Applications. In *Proceedings of the 2004 symposium on Eye tracking research \& applications*, pages 11–18.
- Kán, P. and Kaufmann, H. (2012). Physically-Based Depth of Field in Augmented Reality. In *Eurographics (Short Papers)*, pages 89–92.
- Katz, S. D. (1991). *Film directing shot by shot: visualizing from concept to screen*. Gulf Professional Publishing.

- Kern, D., Marshall, P., and Schmidt, A. (2010). Gazemarks - Gaze-Based Visual Placeholders to Ease Attention Switching. *Group*, pages 2093–2102.
- Kindlmann, G., Reinhard, E., Creem, S., Kindlmann, G., Reinhard, E., and Creem, S. (2002). Face-based luminance matching for perceptual colormap generation. In *Proceedings of the conference on Visualization, VIS '02*, pages 299–306, Washington, DC, USA. IEEE, IEEE Computer Society.
- Kohler, I. (1963). The formation and transformation of the perceptual world. *Psychological issues*.
- Kolb, C., Mitchell, D., and Hanrahan, P. (1995). A Realistic Camera Model for Computer Graphics. In *Proceedings of the 22nd annual conference on Computer graphics and interactive techniques*, pages 317–324, New York, New York, USA. ACM.
- Kortum, P. and Geisler, W. (1996). Implementation of a foveated image coding system for image bandwidth reduction. In Rogowitz, B. E. and Allebach, J. P., editors, *SPIE Proceedings*, volume 2657, pages 350–360.
- Lambooi, M., IJsselsteijn, W., Fortuin, M., and Heynderickx, I. (2009). Visual Discomfort and Visual Fatigue of Stereoscopic Displays: A Review. *Journal of Imaging Science and Technology*, 53(3):030201.
- Lee, S., Eisemann, E., and Seidel, H.-P. (2010). Real-time Lens Blur Effects and Focus Control. *ACM Transactions on Graphics*, 29(4):65:1–65:7.
- Leroy, L., Fuchs, P., and Moreau, G. (2012). Real-time adaptive blur for reducing eye strain in stereoscopic displays. In *Transactions on Applied Perception*, page 9. ACM.
- Levoy, M. and Whitaker, R. (1990). Gaze-directed volume rendering. *ACM SIGGRAPH Computer Graphics*.
- Loschky, L. C. and McConkie, G. W. (2000). User performance with gaze contingent multiresolutional displays. *Proceedings of the 2000 symposium on Eye tracking research & applications*.

- Luebke, D. and Erikson, C. (1997). View-dependent simplification of arbitrary polygonal environments. *Proceedings of the 24th annual conference on Computer graphics and interactive techniques - SIGGRAPH '97*, pages 199–208.
- Luebke, D., Hallen, B., Newfield, D., and Watson, B. (2001). *Perceptually Driven Simplification Using Gaze-Directed Rendering*. Springer.
- Mansencal, T., Mauderer, M., and Parsons, M. (2015). Colour 0.3.6.
- Mantiuk, R., Bazyluk, B., and Tomaszewska, A. (2011). Gaze-Dependent depth-of-field effect rendering in virtual environments. In *Proc. of Serious Games Development and Applications*, volume 6944 of *Lecture Notes in Computer Science*, pages 1–12. Springer.
- Mantiuk, R. R. and Markowski, M. (2013). Gaze-Dependent Tone Mapping. In *Image Analysis and Recognition*, pages 426–433. Springer.
- Mao, X. and Watanabe, D. (2004). Gaze-directed flow visualization. *Electronic Imaging*, pages 141–150.
- Marshall, J. a., Burbeck, C. a., Ariely, D., Rolland, J. P., and Martin, K. E. (1996). Occlusion edge blur: a cue to relative visual depth. *Journal of the Optical Society of America A*, 13(4):681–8.
- Mather, G. (1996). Image blur as a pictorial depth cue. *Royal Society of London Proceedings Series B*, 263(1367):169–72.
- Mather, G. (1997). The use of image blur as a depth cue. *Perception*, 26(9):1147–58.
- Mather, G. and Smith, D. R. (2004). Combining depth cues: effects upon accuracy and speed of performance in a depth-ordering task. *Vision Research*, 44(6):557–562.
- Mather, G. and Smith, D. R. R. (2002). Blur discrimination and its relation to blur-mediated depth perception. *Perception*, 31(10):1211–1219.
- Mauderer, M., Conte, S., Nacenta, M. A., and Vishwanath, D. (2014). Depth perception with gaze-contingent depth of field. In *Proceedings of the ACM conference on Human factors in computing systems*, pages 217–226, New York, New York, USA. ACM, ACM Press.

REFERENCES

- Mauderer, M., Flatla, D. R., and Nacenta, M. A. (2016). Gaze-contingent Manipulation of Color Perception. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, New York, New York, USA. ACM.
- McConkie, G. W. and Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics*, 17(6):578–586.
- McNamara, A., Bailey, R., and Grimm, C. (2008). Improving search task performance using subtle gaze direction. In *Proceedings of the symposium on Applied perception in graphics and visualization*, volume 6, page 51, New York, New York, USA. ACM Press.
- McNamara, A., Booth, T., and Sridharan, S. (2012). Directing gaze in narrative art. In *Proceedings of the ACM Symposium on Applied Perception - SAP '12*, page 63, New York, New York, USA. ACM Press.
- Millman, K. J. and Aivazis, M. (2011). Python for Scientists and Engineers. *Computing in Science Engineering*, 13(2):9–12.
- Morimoto, C. H. and Mimica, M. R. M. (2005). Eye gaze tracking techniques for interactive applications. *Computer Vision and Image Understanding*, 98(1):4–24.
- Moroney, N., Fairchild, M. D., Hunt, R. W. G., Li, C., Luo, M. R., and Newman, T. (2002). The CIECAM02 color appearance model. In *Color and Imaging Conference*, number 1, pages 23–27. Society for Imaging Science and Technology.
- Munsell, A. H. (1950). *Munsell book of color*. Munsell Color Co.
- Murakami, K., Jalkh, A. E., Avila, M. P., Trempe, C. L., and Schepens, C. L. (1983). Vitreous floaters. *Ophthalmology*, 90(11):1271–6.
- Murphy, H. and Duchowski, A. T. (2001). Gaze-contingent level of detail rendering. *Eurographics*.
- Nefs, H. T. (2012). Depth of Field Affects Perceived Depth-width Ratios in Photographs of Natural Scenes. *Seeing and Perceiving*, 25(6):577–595.
- Nickerson, D. (1940). History of the Munsell color system and its scientific application. *Journal of the Optical Society of America*, 30:575.

- Norrby, S., Piers, P., Campbell, C., and van der Mooren, M. (2007). Model eyes for evaluation of intraocular lenses. *Applied optics*, 46(26):6595–605.
- Ogboso, Y. U. and Bedell, H. E. (1987). Magnitude of lateral chromatic aberration across the retina of the human eye. *Journal of the Optical Society of America. A, Optics and image science*, 4(8):1666–1672.
- Ohshima, T., Yamamoto, H., and Tamura, H. (1996). Gaze-directed adaptive rendering for interacting with virtual space. In *Proceedings of the IEEE 1996 Virtual Reality Annual International Symposium*, pages 103–111. IEEE.
- O’Shea, R. P., Govan, D. G., and Sekuler, R. (1997). Blur and contrast as pictorial depth cues. *Perception*, 26(5):599–612.
- O’Sullivan, C. and Dingliana, J. (2001). Collisions and perception. *ACM Transactions on Graphics*, 20(3):151–168.
- O’Sullivan, C., Dingliana, J., and Howlett, S. (2002). Eye movements and interactive graphics. *The Mind’s Eyes*.
- O’Sullivan, C., Howlett, S., McDonnell, R., Morvan, Y., Conor, K. O., Sullivan, C. O., Howlett, S., McDonnell, R., Morvan, Y., and Conor, K. O. (2004). Perceptually Adaptive Graphics. *Eurographics state-of-the-art-reports*.
- Otani, K., Yoshida, T., Nii, H., Kawakami, N., and Tachi, S. (2008). Active Focus Control with Eye Gaze Detection for Depth Cognition. In *ASIAGRAPH 2008*.
- Otazu, X., Penacchio, O., and Dempere-Marco, L. (2012). Brightness induction by contextual influences in V1: a neurodynamical account. *Journal of Vision*, 12(9):1208–1208.
- Parkhurst, D. and Niebur, E. (2003). A Feasibility Test for Perceptually Adaptive Level of Detail Rendering on Desktop Systems. In *Proceedings of the 1st Symposium on Applied perception in graphics and visualization*, pages 49–56. ACM.
- Parkhurst, D. J. and Niebur, E. (2002). Variable-Resolution Displays: A Theoretical, Practical, and Behavioral Evaluation. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 44(4):611–629.

REFERENCES

- Peirce, J. W. (2009). Generating stimuli for neuroscience using PsychoPy. *Frontiers in Neuroinformatics*, 2(10).
- Perry, J. S. and Geisler, W. S. (2002). Gaze-contingent real-time simulation of arbitrary visual fields. In Rogowitz, B. E. and Pappas, T. N., editors, *Proceedings SPIE*, volume 4662, pages 57–69. International Society for Optics and Photonics.
- Potmesil, M. and Chakravarty, I. (1981). A lens and aperture camera model for synthetic image generation. In *ACM SIGGRAPH Computer Graphics*, volume 15, pages 297–305.
- Qvarfordt, P., Biehl, J. T. J. T., Golovchinsky, G., and Dunningan, T. (2010). Understanding the benefits of gaze enhanced visual search. *Proceedings of the 2010 Symposium on Eye-Tracking Research & Applications - ETRA '10*, page 283.
- Rahardja, S., Farbiz, F., Manders, C., Zhiyong, H., Ling, J. N. S., Khan, I. R., Ping, O. E., and Peng, S. (2009). Eye HDR: Gaze-adaptive system for displaying high-dynamic-range images. *SIGGRAPH ASIA Art Gallery & Emerging Technologies*, page 68–68.
- Rayner, K. (1975). The perceptual span and peripheral cues in reading. *Cognitive Psychology*, 7(1):65–81.
- Rayner, K. (2014). The gaze-contingent moving window in reading: Development and review. *Visual Cognition*, 00(00):1–17.
- Rayner, K., Castelhano, M. S., and Yang, J. (2009). Eye movements and the perceptual span in older and younger readers. *Psychology and aging*, 24(3):755.
- Reddy, M. (1998). Specification and evaluation of level of detail selection criteria. *Virtual Reality*, 3(2):132–143.
- Reingold, E. M., Loschky, L. C., McConkie, G. W., and Stampe, D. M. (2003). Gaze-contingent multiresolutional displays: an integrative review. *Human factors*, 45(2):307–328.
- Reinhard, E., Heidrich, W., Debevec, P., Pattanaik, S., Ward, G., and Myszkowski, K. (2010). *High dynamic range imaging: acquisition, display, and image-based lighting*. Morgan Kaufmann, 1 edition.

- Richards, W. (1970). Stereopsis and stereoblindness. *Experimental Brain Research*, 10(4):380–8.
- Robertson, A. R. (1977). The CIE 1976 Color-Difference Formulae. *Color Research & Application*, 2(1):7–11.
- Robertson, A. R. (1990). Historical development of CIE recommended color difference equations. *Color Research & Application*, 15(3):167–170.
- Robinson, D. A. (1963). A method of measuring eye movement using a scleral search coil in a magnetic field. *Bio-medical Electronics, IEEE Transactions on*, 10(4):137–145.
- Rokita, P. (1996). Generating depth of-field effects in virtual reality applications. In *Proc. of Computer Graphics and Applications*, pages 18–21.
- Sanson, G. D., Read, J., Simpson, S. J., Wang, S., Joern, A., Sword, G. a., Chen, Y. L., Behmer, S. T., Blanckenhorn, W. U., Korner, C., Raubenheimer, D., Wu, J., Yong, S., Yang, J., Yong, W., Overton, C., Niren, D., Flynn, D., Kong, Y., Fan, Z., Esman, J., Chen, Q., Zhang, G., Quinlan, M., Denardo, D., Vandenbrooks, J., Klok, C., Behmer, S., Mccrackin, M., Clissold, F., and Xi, S. (2012). Depth Perception from Image Defocus in a Jumping Spider. *Organization*, 335(January):469–471.
- Schaeffel, F., Wilhelm, H., and Zrenner, E. (1993). Inter-individual variability in the dynamics of natural accommodation in humans: relation to age and refractive errors. *The Journal of Physiology*, 32:301–320.
- Skodras, A., Christopoulos, C., and Ebrahimi, T. (2001). The JPEG 2000 still image compression standard. *Signal Processing Magazine*, 18(5):36–58.
- Smith, T. and Guild, J. (1931). The C.I.E. colorimetric standards and their use. *Transactions of the Optical Society*, 33(3):73.
- Spence, I., Kutlesa, N., and Rose, D. L. (1999). Using Color to Code Quantity in Spatial Displays. *Journal of Experimental Psychology: Applied*, 5(4):393–412.
- Sridharan, S., McNamara, A., Grimm, C., Bailey, R., and Costello, A. (2012). Subtle gaze manipulation for improved mammography training. In *Proceedings of the Symposium on Eye Tracking Research and Applications*, number 212, pages 75–82, New York, New York, USA. ACM Press.

REFERENCES

- Steinert, B., Dammertz, H., Hanika, J., and Lensch, H. P. A. (2011). General spectral camera lens simulation. In *Computer Graphics Forum*, number 6, pages 1643–1654. Wiley Online Library.
- Stellmach, S. and Dachsel, R. (2012). Look & Touch : Gaze-supported Target Acquisition. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2981–2990.
- Stockman, a., MacLeod, D. I., and Johnson, N. E. (1993). Spectral sensitivities of the human cones. *Journal of the Optical Society of America. A, Optics, image science, and vision*, 10(12):2491–2521.
- Sun, G. and Holliman, N. (2009). Evaluating methods for controlling depth perception in stereoscopic cinematography. In Woods, A. J., Holliman, N. S., and Merritt, J. O., editors, *Proc. Stereoscopic Displays and Virtual Reality Systems*. SPIE.
- Temme, L. A. and Morris, A. (1989). Speed of accommodation and age. *Optometry & Vision Science*.
- Thibos, L. N., Ye, M., Zhang, X., and Bradley, A. (1992). The chromatic eye: a new reduced-eye model of ocular chromatic aberration in humans. *Applied Optics*, 31(19):3594.
- Toet, A. (2006). Gaze directed displays as an enabling technology for attention aware systems. *Computers in Human Behavior*, 22(4):615–647.
- Van Der Walt, S., Schönberger, J. L., Nunez-Iglesias, J., Boulogne, F., Warner, J. D., Yager, N., Gouillart, E., and Yu, T. (2014). scikit-image: image processing in Python. *PeerJ*, 2:e453.
- Vinnikov, M. and Allison, R. S. (2014). Gaze-contingent Depth of Field in Realistic Scenes: The User Experience. In *Proceedings of the Symposium on Eye Tracking Research and Applications, ETRA '14*, pages 119–126, New York, NY, USA. ACM.
- Vishwanath, D. and Blaser, E. (2010). Retinal blur and the perception of egocentric distance. *Journal of Vision*, 10:1–16.
- Wade, N. J. and Tatler, B. W. (2009). Did Javal measure eye movements during reading? *Journal of Eye Movement Research*, 2(5):1–7.

- Wallace, G. K. (1991). The JPEG still picture compression standard. *Communications of the ACM*, 34(4):30–44.
- Walt, S. v. d., Colbert, S. C., Varoquaux, G., van der Walt, S., Colbert, S. C., and Varoquaux, G. (2011). The NumPy Array: A Structure for Efficient Numerical Computation. *Computing in Science Engineering*, 13(2):22–30.
- Wang, B. and Ciuffreda, K. J. (2006). Depth-of-focus of the human eye: theory and clinical implications. *Survey of ophthalmology*, 51(1):75–85.
- Wang, J., Barkowsky, M., Ricordel, V., and Le Callet, P. (2011). Quantifying how the combination of blur and disparity affects the perceived depth. In *Proc. of Electronic Imaging*. SPIE.
- Watson, B. and Hodges, L. F. (2004). Supra-Threshold Control of Peripheral LOD. *ACM Transactions on Graphics (TOG)*, 1(212):750–759.
- Watt, S. J., Akeley, K., Ernst, M. O., and Banks, M. S. (2005). Focus cues affect perceived depth. *Journal of vision*, 5(10):834–62.
- Weeber, H., Terwee, T., van der Mooren, M., and Piers, P. (2008). Visualization of the retinal image in an eye model with spherical and aspheric, diffractive, and refractive multifocal intraocular lenses. *Journal of refractive surgery*, 24(3):223–232.
- Williams, N., Luebke, D., Cohen, J. D., Kelley, M., and Schubert, B. (2003). Perceptually guided simplification of lit, textured meshes. *Proceedings of the 2003 symposium on Interactive 3D graphics - SI3D '03*, page 113.
- Winn, B., Bradley, A., Strang, N. C., McGraw, P. V., and Thibos, L. N. (1995). Reversals of the colour-depth illusion explained by ocular chromatic aberration. *Vision Research*, 35(19):2675–2684.
- Witt, J. K., Proffitt, D. R., and Epstein, W. (2005). Tool use affects perceived distance, but only when you intend to use it. *Journal of Experimental Psychology: Human Perception and Performance*, 31(5):880.
- Wu, J., Zheng, C., Hu, X., Wang, Y., and Zhang, L. (2010). Realistic rendering of bokeh effect based on optical aberrations. *The Visual Computer*, 26(6):555–563.

REFERENCES

- Yamauchi, T., Mikami, T., and Ouda, O. (2011). Improvement and evaluation of real-time tone mapping for high dynamic range images using gaze information. *Computer Vision - ACCV 2010 Workshops*, pages 440–449.
- Young, L. R. and Sheena, D. (1975). Survey of eye movement recording methods. *Behavior Research Methods & Instrumentation*, 7(5):397–429.

VVI

PART VI

APPENDIX



APPENDIX A

ETHICAL APPROVAL FOR RESEARCH

This appendix contains the letters of approval from the University Teaching and Research Ethics committee. This includes the letter of approval for the experiments on depth perception (Appendix A.1) and colour perception (Appendix A.2).

A.1 Letter of approval for studies on gaze-contingent depth perception



29/05/2012
Miguel Nacenta
School Of Computer Science

Ethics Reference No: <i>Please quote this ref on all correspondence</i>	CS8778
Project Title:	Investigation of visual processes and viewer experience using gaze contingent displays and depth cues (DEEVIEW)
Researchers Name(s):	Miguel Nacenta, Dhanraj Vishwanath, Julie Harris, Paul Cox (student), Simone Conte (student) – Students are research assistants, research not part of their coursework or dissertations.
Supervisor(s):	Miguel Nacenta

Thank you for submitting your application which was considered at the School of Computer Science - School Ethics Committee meeting on the 29/05/2012. The following documents were reviewed:

1. Ethical Application Form
2. Participant Information Sheet
3. Consent Form
4. Advertisement-Experiment
5. Advertisement-Email

The University Teaching and Research Ethics Committee (UTREC) approves this study from an ethical point of view. Please note that where approval is given by a School Ethics Committee that committee is part of UTREC and is delegated to act for UTREC.

Approval is given for three years. Projects, which have not commenced within two years of original approval, must be re-submitted to your School Ethics Committee.

You must inform your School Ethics Committee when the research has been completed. If you are unable to complete your research within the 3 three year validation period, you will be required to write to your School Ethics Committee and to UTREC (where approval was given by UTREC) to request an extension or you will need to re-apply.

Any serious adverse events or significant change which occurs in connection with this study and/or which may alter its ethical consideration, must be reported immediately to the School Ethics Committee, and an Ethical Amendment Form submitted where appropriate.

Approval is given on the understanding that the 'Guidelines for Ethical Research Practice' (<http://www.st-andrews.ac.uk/media/UTRECguidelines%20Feb%2008.pdf>) are adhered to.

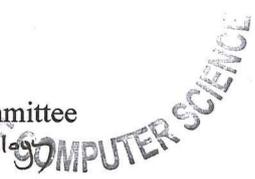
Yours sincerely

Convener of the School Ethics Committee

OR

Convener of UTREC

Ccs
Supervisor
School Ethics Committee
School of Psychology



A.2 Letter of approval for studies on gaze-contingent colour perception



University of St Andrews

Scotland's first university – 1413

University Teaching and Research Ethics Committee Sub-committee

16th October 2014
 Michael Mauderer
 School of Computer Science

Ethics Reference No: <i>Please quote this ref on all correspondence</i>	CS11186
Project Title:	A Study on Gaze-contingent colour manipulation
Researchers Name(s):	Michael Mauderer, Dr David Flatla, Dr Miguel Nacenta
Supervisor(s):	Dr Miguel Nacenta

Thank you for submitting your application which was considered at the Computer Science School Ethics Committee meeting on the 16th October 2014. The following documents were reviewed:

- | | |
|-------------------------------------------|---------------------------------|
| 1. Ethical Application Form | 24 th September 2014 |
| 2. Participant Information Sheet | 24 th September 2014 |
| 3. Consent Form | 24 th September 2014 |
| 4. Debriefing Form | 24 th September 2014 |
| 5. Demographic Information Survey | 24 th September 2014 |
| 6. Sample Advertisement
(as necessary) | 24 th September 2014 |

The University Teaching and Research Ethics Committee (UTREC) approve this study from an ethical point of view. Please note that where approval is given by a School Ethics Committee that committee is part of UTREC and is delegated to act for UTREC.

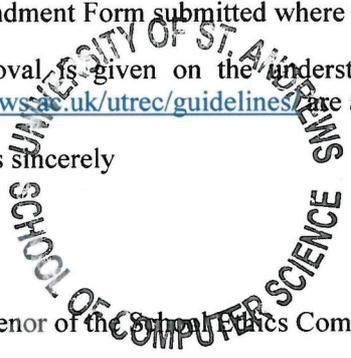
Approval is given for three years. Projects, which have not commenced within two years of original approval, must be re-submitted to your School Ethics Committee.

You must inform your School Ethics Committee when the research has been completed. If you are unable to complete your research within the 3 three year validation period, you will be required to write to your School Ethics Committee and to UTREC (where approval was given by UTREC) to request an extension or you will need to re-apply.

Any serious adverse events or significant change which occurs in connection with this study and/or which may alter its ethical consideration must be reported immediately to the School Ethics Committee, and an Ethical Amendment Form submitted where appropriate.

Approval is given on the understanding that the 'Guidelines for Ethical Research Practice' <https://www.st-andrews.ac.uk/utrec/guidelines> are adhered to.

Yours sincerely



Convener of the School Ethics Committee

Ccs Supervisor
 School Ethics Committee

APPENDIX B

STUDY MATERIAL FOR EXPERIMENT ON GAZE-CONTINGENT DEPTH OF FIELD

This appendix contains the study material used in the experiment on gaze-contingent depth of field described in Chapter 4. This includes the participant information sheet (Appendix B.1), anonymous data consent form (Appendix B.2) and the demographic information questionnaire (Appendix B.3).

B.1 Participant Information Sheet

Investigation of visual processes and viewer experience using gaze-contingent displays (DEEVIEW)

What is the study about?

We invite you to participate in a research project about visual perception using gaze contingent displays. This research is about how the characteristics of dynamic displays can affect the visual experience and the perception of scenes.

This study is being conducted as part of our research in perception and human-computer interaction in the Schools of Computer Science and Psychology.

Do I have to take Part?

This information sheet has been written to help you decide if you would like to take part. It is up to you and you alone whether or not to take part. If you do decide to take part you will be free to withdraw at any time without providing a reason.

What would I be required to do?

First we will collect some personal information such as your age, your area of study and your experience with different kinds of displays. After this we will perform a test of your acuity. Then we will start the eye tracking experiment with a short tutorial familiarizing you with the equipment and the following task. During the experiment you will have to judge the position of two objects in a 3D scene using sliders.

Will my participation be Anonymous and Confidential?

Your participation in this study is anonymous. Only the researcher(s) and supervisor(s) will have access to the raw data, which will be kept strictly confidential. Your permission is sought in the Participant Consent form for the data you provide, which will be anonymised, to be used for future scholarly purposes.

Storage and Destruction of Data Collected

The raw data we collect will be accessible by the researchers involved in this study only and to the students named above and other students supervised by the researchers. In the consent form we ask your explicit consent for making the data public as research publications in an anonymised form. Your identity will not be linked to the data we collect from the experiment in any of these publications, and only the researchers will be able to connect the data collected to your identity. Your data will be stored indefinitely, and it will be stored in an anonymised format on a computer system that will be accessible only to the researchers. Paper forms will be stored in a locked storage cupboard.

What will happen to the results of the research study?

The results will be analysed and written up as part of our research in scientific publications and or technical reports.

Reward and benefits

In compensation for your time you will receive a compensation of an Amazon voucher for £8. By participating in this study you will help advance scientific knowledge on perception and human-computer interaction that can result in benefits for individuals and society.

Are there any potential risks to taking part?

There are no known harms or risks associated to the participation in this study.

Questions

You will have the opportunity to ask any questions in relation to this project before giving completing a Consent Form. During the study you can omit questions that you do not want to answer.

Consent and Approval

This research proposal has been granted Ethical Approval through the University ethical approval process.

What should I do if I have concerns about this study?

A full outline of the procedures governed by the University Teaching and Research Ethical Committee is available at <http://www.st-andrews.ac.uk/utrec/complaints/>

Contact Details

Michael Mauderer	mm285@st-andrews.ac.uk	+44 (0)1334 463260
Dr. Miguel Nacenta	miguel.nacenta@st-andrews.ac.uk	+44 (0) 1334 46 32 65
Dr. Dhanraj Vishwanath	dv10@st-andrews.ac.uk	+44 (0)1334 462074

B.2 Participant Consent Form



Participant Consent Form

Coded Data

Project Title

Investigation of visual processes and viewer experience using gaze contingent displays and depth cues (DEEVIEW)

Researchers Names

Michael Mauderer	mm285@st-andrews.ac.uk	+44 (0)1334 463260
Dr. Miguel Nacenta	miguel.nacenta@st-andrews.ac.uk	+44 (0) 1334 46 32 65
Dr. Dhanraj Vishwanath	dv10@st-andrews.ac.uk	+44 (0)1334 462074

The University of St Andrews attaches high priority to the ethical conduct of research. We therefore ask you to consider the following points before signing this form. Your signature confirms that you are happy to participate in the study.

What is Coded Data?

The term 'Coded Data' refers to when data collected by the researcher is identifiable as belonging to a particular participant but is kept with personal identifiers removed. The researcher(s) retain a 'key' to the coded data which allows individual participants to be re-connected with their data at a later date. The un-coded data is kept confidential to the researcher(s) (and Supervisors). If consent is given to archive data (see consent section of form) the participant may be contacted in the future by the original researcher(s) or other researcher(s).

Consent

The purpose of this form is to ensure that you are willing to take part in this study and to let you understand what it entails. Signing this form does not commit you to anything you do not wish to do and you are free to withdraw at any stage.

Material gathered during this research will be coded and kept confidentially by the researchers with only the researchers having access. It will be securely stored in a hard drive to which only the researchers will have physical and virtual access.

Please answer each statement concerning the collection and use of the research data.

I have read and understood the information sheet.	<input type="checkbox"/> Yes	<input type="checkbox"/> No
I have been given the opportunity to ask questions about the study.	<input type="checkbox"/> Yes	<input type="checkbox"/> No
I have had my questions answered satisfactorily.	<input type="checkbox"/> Yes	<input type="checkbox"/> No
I understand that I can withdraw from the study at any time without having to give an explanation.	<input type="checkbox"/> Yes	<input type="checkbox"/> No
I understand that my data will be confidential and that it will contain identifiable personal data but that will be stored with personal identifiers removed by the researcher and that only the researcher/supervisor will be able to decode this information as and when necessary.	<input type="checkbox"/> Yes	<input type="checkbox"/> No
<i>I understand that my data will be stored indefinitely</i> I have been made fully aware of the potential risks associated with this research and am satisfied with the information provided.	<input type="checkbox"/> Yes	<input type="checkbox"/> No
I agree to take part in the study	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Participation in this research is completely voluntary and your consent is required before you can participate in this research.		
If you decide at a later date that data should be destroyed we will honour your request in writing.		

Name in Block Capitals

Signature.....

-

Date.....

-

B.3 Demographic Information Questionnaire

Questionnaire

Age _____

Gender female male

Vision Glasses Contact lenses None

Handedness left right

Dominant Eye left right

Acuity (Near) _____

Acuity (Far) _____

STUDY MATERIAL FOR EXPERIMENT ON GAZE-CONTINGENT CHROMATIC ABERRATION

This section contains the study material used in the experiment on gaze-contingent chromatic aberration described in Chapter 5. This includes the participant information sheet (Appendix C.1), anonymous data consent form (Appendix C.2), the demographic information questionnaire (Appendix C.3) and the post experiment questionnaire.

C.1 Participant Information Sheet

Investigation of visual processes and viewer experience using gaze-contingent displays (DEEVIEW)

What is the study about?

We invite you to participate in a research project about visual perception using gaze contingent displays. This research is about how the characteristics of dynamic displays can affect the visual experience and the perception of scenes.

This study is being conducted as part of our research in perception and human-computer interaction in the Schools of Computer Science and Psychology.

Do I have to take Part?

This information sheet has been written to help you decide if you would like to take part. It is up to you and you alone whether or not to take part. If you do decide to take part you will be free to withdraw at any time without providing a reason.

What would I be required to do?

First we will collect some personal information such as your age, your area of study and your experience with different kinds of displays. After this we will perform a test of your acuity. Then we will start the eye tracking experiment with a short tutorial familiarizing you with the equipment and the following task. During the experiment you will have to judge the position of two objects in a 3D scene using sliders.

Will my participation be Anonymous and Confidential?

Your participation in this study is anonymous. Only the researcher(s) and supervisor(s) will have access to the raw data, which will be kept strictly confidential. Your permission is sought in the Participant Consent form for the data you provide, which will be anonymised, to be used for future scholarly purposes.

Storage and Destruction of Data Collected

The raw data we collect will be accessible by the researchers involved in this study only and to the students named above and other students supervised by the researchers. In the consent form we ask your explicit consent for making the data public as research publications in an anonymised form. Your identity will not be linked to the data we collect from the experiment in any of these publications, and only the researchers will be able to connect the data collected to your identity. Your data will be stored indefinitely, and it will be stored in an anonymised format on a computer system that will be accessible only to the researchers. Paper forms will be stored in a locked storage cupboard.

What will happen to the results of the research study?

The results will be analysed and written up as part of our research in scientific publications and or technical reports.

Reward and benefits

In compensation for your time you will receive a compensation of an Amazon voucher for £8. By participating in this study you will help advance scientific knowledge on perception and human-computer interaction that can result in benefits for individuals and society.

Are there any potential risks to taking part?

There are no known harms or risks associated to the participation in this study.

Questions

You will have the opportunity to ask any questions in relation to this project before giving completing a Consent Form. During the study you can omit questions that you do not want to answer.

Consent and Approval

This research proposal has been granted Ethical Approval through the University ethical approval process.

What should I do if I have concerns about this study?

A full outline of the procedures governed by the University Teaching and Research Ethical Committee is available at <http://www.st-andrews.ac.uk/utrec/complaints/>

Contact Details

Michael Mauderer	mm285@st-andrews.ac.uk	+44 (0)1334 463260
Dr. Miguel Nacenta	miguel.nacenta@st-andrews.ac.uk	+44 (0) 1334 46 32 65
Dr. Dhanraj Vishwanath	dv10@st-andrews.ac.uk	+44 (0)1334 462074

C.2 Participant Consent Form



Participant Consent Form

Coded Data

Project Title

Investigation of visual processes and viewer experience using gaze contingent displays and depth cues (DEEVIEW)

Researchers Names

Michael Mauderer	mm285@st-andrews.ac.uk	+44 (0)1334 463260
Dr. Miguel Nacenta	miguel.nacenta@st-andrews.ac.uk	+44 (0) 1334 46 32 65
Dr. Dhanraj Vishwanath	dv10@st-andrews.ac.uk	+44 (0)1334 462074

The University of St Andrews attaches high priority to the ethical conduct of research. We therefore ask you to consider the following points before signing this form. Your signature confirms that you are happy to participate in the study.

What is Coded Data?

The term 'Coded Data' refers to when data collected by the researcher is identifiable as belonging to a particular participant but is kept with personal identifiers removed. The researcher(s) retain a 'key' to the coded data which allows individual participants to be re-connected with their data at a later date. The un-coded data is kept confidential to the researcher(s) (and Supervisors). If consent is given to archive data (see consent section of form) the participant may be contacted in the future by the original researcher(s) or other researcher(s).

Consent

The purpose of this form is to ensure that you are willing to take part in this study and to let you understand what it entails. Signing this form does not commit you to anything you do not wish to do and you are free to withdraw at any stage.

Material gathered during this research will be coded and kept confidentially by the researchers with only the researchers having access. It will be securely stored in a hard drive to which only the researchers will have physical and virtual access.

Please answer each statement concerning the collection and use of the research data.

I have read and understood the information sheet.	<input type="checkbox"/> Yes	<input type="checkbox"/> No
I have been given the opportunity to ask questions about the study.	<input type="checkbox"/> Yes	<input type="checkbox"/> No
I have had my questions answered satisfactorily.	<input type="checkbox"/> Yes	<input type="checkbox"/> No
I understand that I can withdraw from the study at any time without having to give an explanation.	<input type="checkbox"/> Yes	<input type="checkbox"/> No
I understand that my data will be confidential and that it will contain identifiable personal data but that will be stored with personal identifiers removed by the researcher and that only the researcher/supervisor will be able to decode this information as and when necessary.	<input type="checkbox"/> Yes	<input type="checkbox"/> No
<i>I understand that my data will be stored indefinitely</i> I have been made fully aware of the potential risks associated with this research and am satisfied with the information provided.	<input type="checkbox"/> Yes	<input type="checkbox"/> No
I agree to take part in the study	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Participation in this research is completely voluntary and your consent is required before you can participate in this research.		
If you decide at a later date that data should be destroyed we will honour your request in writing.		

Name in Block Capitals

Signature.....

-

Date.....

-

C.3 Demographic Information Questionnaire

Questionnaire

Age _____

Gender female male

Vision Glasses Contact lenses None

Handedness left right

Dominant Eye left right

Acuity (Near) _____

Acuity (Far) _____

C.4 Post Experiment Questionnaire

Questionnaire Part 2

Did you notice any anomalies or unexpected things while looking at the display during the experiment (e.g., movements or flickering)?

Did you find a strategy that helped you to determine the depth of the objects?

If so could you describe the strategy?

STUDY MATERIAL FOR EXPERIMENT ON GAZE-CONTINGENT COLOUR MATCHING

This section contains the study material used in the experiment on gaze-contingent colour matching in Chapter 6. This includes the participant information sheet (Appendix D.1), the anonymous data consent form (Appendix D.2), the debriefing form (Appendix D.3), the debriefing survey (appendix D.4) and the demographic information questionnaire (Appendix D.5)

D.1 Participant Information Sheet



Participant Information Sheet

Project Title

A Study on Gaze-contingent colour manipulation (Part 3)

What is the study about?

We invite you to participate in a research project about visual perception using gaze contingent displays. This research is about how the characteristics of dynamic displays can affect the visual experience and the perception of colour.

This study is being conducted as part of the Ph.D. research of Michael Mauderer, advised by Dr. Miguel Nacenta, in the School of Computer Science.

Do I have to take Part?

This information sheet has been written to help you decide if you would like to take part. It is up to you and you alone whether or not to take part. If you do decide to take part you will be free to withdraw at any time without providing a reason.

What would I be required to do?

First you will be asked to fill in a basic questionnaire of personal data including gender, age, visual ability, use of your computer, and use of computer games. We will also test you for visual acuity and colour ability.

This experiment consists of a simple colour matching task that is performed on a computer with an attached eye tracker. The task will require you to use a slider to change the appearance of a colour patch to match a reference colour.

The experiment will start with an introduction and explain the task and interface to you. After that there will be two blocks: One where the presented display is static and one where the display will change in response to your eye movement.

At the end of the experiment we will provide you with a £5 pound Amazon voucher and with a debriefing form.

We expect that the full experiment will take about 30min to complete.

Will my participation be Anonymous and Confidential?

Only the researcher(s) and supervisor(s) will have access to the raw data which will be kept strictly confidential. Your permission is sought in the Participant Consent form for the data you provide, which will be anonymised, to be used for future scholarly purposes.

Storage and Destruction of Data Collected

The raw data that we collect will be accessible by the researcher(s) involved in this study only. The anonymised data from the experiment, which includes recorded input and trial measures (accuracy, completion time of each trial) will be analysed and published, but without any link to your name or identity. The raw data will be stored for a period of maximum 4 years before being destroyed, in a locked filing cabinet and in secured computer systems. The anonymised data may be published and shared with other researchers in a number of ways, including the Internet.

What will happen to the results of the research study?

The results will be analysed and written up as one or many publications in scientific journals and conferences.

Reward

To thank you for your participation we will provide you with a £5 Amazon.co.uk gift voucher.

Are there any potential risks to taking part?

We know of no risks for participating in this experiment beyond those that you experience in your regular daily life.

Questions

You will have the opportunity to ask any questions in relation to this project before completing a Consent Form.

Consent and Approval

This research proposal has been scrutinised and been granted Ethical Approval through the University ethical approval process.

What should I do if I have concerns about this study?

A full outline of the procedures governed by the University Teaching and Research Ethical Committee is available at <http://www.st-andrews.ac.uk/utrec/Guidelines/complaints/>

Contact Details

*Researcher: Michael Mauderer
Contact Details: mm285@st-andrews.ac.uk*

*Researcher: Dr. Miguel A. Nacenta
Contact Details: mans@st-andrews.ac.uk, tel: 01334 46 32 65*

D.2 Participant Consent Form



Participant Consent Form

Anonymous Data

Project Title

A Study on Gaze-contingent colour manipulation (Part 3)

Researcher(s) Name(s)

Michael Mauderer, Ph.D. student
School of Computer Science, University of St Andrews
John Honey building (North Haugh) room 1.05
mm285@st-andrews.ac.uk

Dr. Miguel Nacenta, lecturer
School of Computer Science, University of St Andrews
Jack Cole building (North Haugh) room 0.11
mans@st-andrews.ac.uk, tel: 01334 46 32 65

The University of St Andrews attaches high priority to the ethical conduct of research. We therefore ask you to consider the following points before signing this form. Your signature confirms that you are happy to participate in the study.

What is Anonymous Data?

The term 'Anonymous Data' refers to data collected by a researcher that has no identifier markers so that even the researcher cannot identify any participant. Consent is still required by the researcher, however no link between the participant's signed consent and the data collected can be made.

Consent

The purpose of this form is to ensure that you are willing to take part in this study and to let you understand what it entails. Signing this form does not commit you to anything you do not wish to do.

Material gathered during this research will be anonymous, so it is impossible to trace back to you. It will be securely stored in a secured computer system and in a locked cabinet for a maximum of 4 years. Please answer each statement concerning the collection and use of the research data.

- I have read and understood the information sheet. Yes No
- I have been given the opportunity to ask questions about the study. Yes No
- I have had my questions answered satisfactorily. Yes No
- I understand that I can withdraw from the study without having to give an explanation. Yes No
- I understand that my data once processed will be anonymous and that only the researcher(s) will have access to the raw data which will be kept confidentially. Yes No
- I understand that my **raw** data will be stored for a period of a maximum of four years before being destroyed and I agree to my **anonymised** data (in line with conditions outlined above) being kept by the researcher and being archived, published and used for further research projects / by other bona fide researchers.* Yes No
- I have been made fully aware of the potential risks associated with this research and am satisfied with the information provided. Yes No
- I agree to take part in the study Yes No

Participation in this research is completely voluntary and your consent is required before you can participate in this research.

Name in Block Capitals _____

Signature _____

Date _____

D.3 Debriefing Form



Debriefing Information Sheet

Project Title

A Study on Gaze-contingent colour manipulation (Part 3)

What is the study about?

This study intends to test how gaze-contingent changes in a display can influence the perception of colour. Our technique changes the display in response to the users' gaze and influences the colour perception by changing the colour of the surrounding area. We are particularly interested in learning about exactly this manipulation influences colour perception.

This work will be submitted for publication in the next few months. If you are interested in getting a copy of the final paper, where we detail the analysis of the results, please send us an e-mail to the first of the addresses below and we will provide you with a copy when it is published.

Thanks again for participating in this study. Without volunteers like you it would be impossible to carry out this kind of research.

Contact Details

Researcher: Michael Mauderer
Contact Details: mm285@st-andrews.ac.uk

Researcher: Dr. Miguel A. Nacenta
Contact Details: mans@st-andrews.ac.uk, tel: 01334 46 32 65

D.4 Debriefing Survey



Debriefing Survey

Project Title

A Study on Gaze-contingent colour manipulation (Part 3)

Did you notice changes or flickering of the presented colour patches during each trial? If so could you describe them?

Did you notice changes or flickering of the background during each trial? If so could you describe them?

D.5 Demographic Information Questionnaire



Demographic Information Survey

Project Title

A Study on Gaze-contingent colour manipulation (Part 3)

Age				_____
Sex	Female	Male		_____
Visual Aid	None	Glasses	Contact lenses	
Handedness		left	right	
Have you participated in one of our earlier colour perception experiments?		yes	no	

Dominant Eye

left

right

Colour perception

Acuity (Near)

Acuity (Far)

APPENDIX E

STUDY MATERIAL FOR EXPERIMENT ON GAZE-CONTINGENT COLOUR SORTING

This section contains the study material used in the experiment on gaze-contingent colour sorting in Chapter 7. This includes the participant information sheet (Appendix E.1), the anonymous data consent form (Appendix E.2), the debriefing form (Appendix E.3), and the demographic information questionnaire (Appendix E.4)

E.1 Participant Information Sheet



Participant Information Sheet

Project Title

A Study on Gaze-contingent colour manipulation (Part 4)

What is the study about?

We invite you to participate in a research project about visual perception using gaze contingent displays. This research is about how the characteristics of dynamic displays can affect the visual experience and the perception of colour.

This study is being conducted as part of the Ph.D. research of Michael Mauderer, advised by Dr. Miguel Nacenta, in the School of Computer Science.

Do I have to take Part?

This information sheet has been written to help you decide if you would like to take part. It is up to you and you alone whether or not to take part. If you do decide to take part you will be free to withdraw at any time without providing a reason.

What would I be required to do?

First you will be asked to fill in a basic questionnaire of personal data including gender, age and visual ability. We will also test you for visual acuity and colour discrimination ability.

This experiment consists of a simple colour sorting task that is performed on a computer with an attached eye tracker. The task will require you to use mouse and keyboard to re-arrange a number of colour patches to fit in a certain order.

The experiment will start with an introduction and explain the task and interface to you. After that there will be multiple blocks with different presentation modes

At the end of the experiment we will provide you with a £5 pound Amazon voucher and with a debriefing form.

We expect that the full experiment will take about 45min to complete.

Will my participation be Anonymous and Confidential?

Only the researcher(s) and supervisor(s) will have access to the raw data which will be kept strictly confidential. Your permission is sought in the Participant Consent form for the data you provide, which will be anonymised, to be used for future scholarly purposes.

Storage and Destruction of Data Collected

The raw data that we collect will be accessible by the researcher(s) involved in this study only. The anonymised data from the experiment, which includes recorded input and trial measures (accuracy, completion time of each trial) will be analysed and published, but without any link to your name or identity. The raw data will be stored for a period of maximum 4 years before being destroyed, in a locked filing cabinet and in secured computer systems. The anonymised data may be published and shared with other researchers in a number of ways, including the Internet.

What will happen to the results of the research study?

The results will be analysed and written up as one or many publications in scientific journals and conferences.

Reward

To thank you for your participation we will provide you with a £5 Amazon.co.uk gift voucher.

Are there any potential risks to taking part?

We know of no risks for participating in this experiment beyond those that you experience in your regular daily life.

Questions

You will have the opportunity to ask any questions in relation to this project before completing a Consent Form.

Consent and Approval

This research proposal has been scrutinised and been granted Ethical Approval through the University ethical approval process.

What should I do if I have concerns about this study?

A full outline of the procedures governed by the University Teaching and Research Ethical Committee is available at <http://www.st-andrews.ac.uk/utrec/Guidelines/complaints/>

Contact Details

*Researcher: Michael Mauderer
Contact Details: mm285@st-andrews.ac.uk*

*Researcher: Dr. Miguel A. Nacenta
Contact Details: mans@st-andrews.ac.uk, tel: 01334 46 32 65*

E.2 Participant Consent Form



Participant Consent Form

Anonymous Data

Project Title

A Study on Gaze-contingent colour manipulation (Part 4)

Researcher(s) Name(s)

Michael Mauderer, Ph.D. student
School of Computer Science, University of St Andrews
John Honey building (North Haugh) room 1.05
mm285@st-andrews.ac.uk

Dr. Miguel Nacenta, lecturer
School of Computer Science, University of St Andrews
Jack Cole building (North Haugh) room 0.11
mans@st-andrews.ac.uk, tel: 01334 46 32 65

The University of St Andrews attaches high priority to the ethical conduct of research. We therefore ask you to consider the following points before signing this form. Your signature confirms that you are happy to participate in the study.

What is Anonymous Data?

The term 'Anonymous Data' refers to data collected by a researcher that has no identifier markers so that even the researcher cannot identify any participant. Consent is still required by the researcher, however no link between the participant's signed consent and the data collected can be made.

Consent

The purpose of this form is to ensure that you are willing to take part in this study and to let you understand what it entails. Signing this form does not commit you to anything you do not wish to do.

Material gathered during this research will be anonymous, so it is impossible to trace back to you. It will be securely stored in a secured computer system and in a locked cabinet for a maximum of 4 years. Please answer each statement concerning the collection and use of the research data.

- I have read and understood the information sheet. Yes No
- I have been given the opportunity to ask questions about the study. Yes No
- I have had my questions answered satisfactorily. Yes No
- I understand that I can withdraw from the study without having to give an explanation. Yes No
- I understand that my data once processed will be anonymous and that only the researcher(s) will have access to the raw data which will be kept confidentially. Yes No
- I understand that my **raw** data will be stored for a period of a maximum of four years before being destroyed and I agree to my **anonymised** data (in line with conditions outlined above) being kept by the researcher and being archived, published and used for further research projects / by other bona fide researchers.* Yes No
- I have been made fully aware of the potential risks associated with this research and am satisfied with the information provided. Yes No
- I agree to take part in the study Yes No

Participation in this research is completely voluntary and your consent is required before you can participate in this research.

Name in Block Capitals _____

Signature _____

Date _____

E.3 Debriefing Form



Debriefing Information Sheet

Project Title

A Study on Gaze-contingent colour manipulation (Part 4)

What is the study about?

This study intends to test how gaze-contingent changes in a display can influence the perception of colour. Our technique changes the display in response to the users' gaze and influences the colour perception by changing the colour of the surrounding area and stimuli. We are particularly interested in learning about exactly this manipulation influences colour perception and how it can be used to the users' benefit.

This work will be submitted for publication in the course of the next year. If you are interested in getting a copy of the final paper, where we detail the analysis of the results, please send us an e-mail to the first of the addresses below and we will provide you with a copy when it is published.

Thanks again for participating in this study. Without volunteers like you it would be impossible to carry out this kind of research.

Contact Details

*Researcher: Michael Mauderer
Contact Details: mm285@st-andrews.ac.uk*

*Researcher: Dr. Miguel A. Nacenta
Contact Details: mans@st-andrews.ac.uk, tel: 01334 46 32 65*

E.4 Demographic Information Questionnaire



Demographic Information Survey

Project Title

A Study on Gaze-contingent colour manipulation (Part 4)

Age				_____
Sex	Female	Male		_____
Visual Aid	None	Glasses	Contact lenses	
Handedness		left	right	
Have you participated in one of our earlier colour perception experiments?		yes	no	

Dominant Eye

left

right

Colour perception

Acuity (Near)

Acuity (Far)

Block 1

Noticed changes in Bg: (Y / N) Patch (Y / N) Used Gaze-Strategy (Y / N)

Block 2

Noticed changes in Bg: (Y / N) Patch (Y / N) Used Gaze-Strategy (Y / N)

Block 3

Noticed changes in Bg: (Y / N) Patch (Y / N) Used Gaze-Strategy (Y / N)

Block 4

Noticed changes in Bg: (Y / N) Patch (Y / N) Used Gaze-Strategy (Y / N)
