

Asymmetry in Spatial Judgments:  
Testing Bin Theory and Spatial Frequency Theory  
in a Double Double Dissociation Design

A Thesis Submitted to  
the College of Graduate Studies and Research  
in Partial Fulfillment of the Requirements  
for the Degree of Doctor of Philosophy  
in the Department of Psychology  
University of Saskatchewan  
Saskatoon

by  
Kathleen M. Goodall

## PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Postgraduate degree from the University of Saskatchewan, I agree that the Libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised my thesis work or, in their absence, by the Head of the Department or the Dean of the College in which my thesis work was done. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my thesis.

Requests for permission to copy or to make other use of material in this thesis in whole or part should be addressed to:

Dr. L. Elias  
Department of Psychology  
9 Campus Drive  
Saskatoon, Saskatchewan  
S7K 5A5

## Abstract

The purpose of this thesis was to determine whether asymmetry in metric and topological spatial judgments could be attributed to the spatial frequency of the stimulus or the size of the attended receptive field. A left hemisphere advantage has been found for topological judgments and a right hemisphere advantage for metric judgments. This asymmetry has been attributed to asymmetrical processing of input conditions, namely size of attended receptive field (called the attentional bin) and spatial frequency of the stimulus. The larger a stimulus, the higher the proportion of low spatial frequencies, so large stimuli are thought to facilitate the extraction of lower spatial frequencies while small stimuli are thought to facilitate the extraction of higher spatial frequencies. A left hemisphere advantage has been reported for high spatial frequencies and small attentional bins and a right hemisphere advantage has been reported for low spatial frequencies and large attentional bins. A method for pitting asymmetrically distributed input conditions against each other using asymmetrically distributed tasks was developed. Three studies were conducted. In the first study, a lack of hemisphere effects suggested bilateral processing of the stimuli. Using an eye tracker, participants were easily able to saccade to the stimulus as was shown in Experiment 2. In Experiment 3, effective exposure duration was reduced so that unilateral viewing was ensured. Under these conditions, bin size and spatial frequency were not dissociable due to a lack of hemisphere effects for spatial frequency and because of task dependency for bin size and spatial frequency processing. Although the assumptions of the double double dissociation were not met, asymmetry in spatial judgments under conditions comparable

to those used by Kosslyn et al.(1989) was attributable to a right hemisphere advantage for processing through small attentional bins.

## Acknowledgments

Many people offered their assistance in the completion of this paper. First and foremost, I wish to thank Dr. Lorin Elias for his very practical help and his invaluable commentary. Second, I wish to thank the members of my dissertation committee, Dr. A. Kirk, Dr. M. Vrbancic, Dr. D. Saucier and Dr. J. Cheesman for their collective support and enthusiasm for this work as well as their useful suggestions and feedback. Third, I owe a great debt of gratitude to Marla Pender, who gathered data, solved problems and maintained, even under great stress, “It’s all good”.

I wish to extend personal appreciation to my parents, Bob and Sandy Goodall, who asked me repeatedly to describe my project and then took the time to write it down so they could continue to refer to it, my in-laws Stan and Laurette Halliwell who provided hours of babysitting at a moment’s notice and my husband who managed to juggle dual roles marvelously well. Finally, I wish to thank my two sons, Ian and Tom, who, as infants, each learned to sleep on a pillow in my lap while I worked on the computer into the night, and as toddlers, put toys in my backpack to take to school with me and, as little boys, learned about the grind of commitment and the ache of delayed gratification all the while holding fast to the dream of future rewards.

## Table of Contents

PERMISSION TO USE .....	i
ABSTRACT .....	ii
ACKNOWLEDGEMENTS .....	iv
TABLE OF CONTENTS .....	v
LIST OF TABLES .....	viii
LIST OF FIGURES .....	ix
LIST OF APPENDICES .....	xi
Preface .....	
1 .....	
 <b>ASYMMETRY IN SPATIAL JUDGMENTS: TESTING BIN THEORY AND SPATIAL FREQUENCY THEORY IN A DOUBLE DOUBLE DISSOCIATION DESIGN</b>	
Overview .....	3
The Evolution of a Percept .....	7
Spatial Frequency Theory .....	10
Procedural Variables .....	
Exposure Duration .....	13
Retinal Eccentricity .....	15
Stimulus Characteristics .....	
Contrast .....	16
Luminance .....	17
Resolution .....	18
Two Process Theory of High Level Visual Processing .....	22
Attentional Bin Theory .....	29
Experiment 1 .....	35
The Double Double Dissociation .....	38
Hypotheses .....	44
Method .....	45
Ethics .....	45
Participants .....	45
Stimuli .....	50

Stimuli Development .....	50
Present Stimuli .....	54
Procedure .....	55
Statistical Analysis .....	58
Results .....	58
Preliminary Analyses .....	61
Reaction Times .....	61
Accuracy .....	62
Reaction Time and Accuracy Correlations .....	62
Normality .....	67
Block Effect .....	67
Block 1 .....	68
Male Participants .....	68
Female Participants .....	69
Block 2 .....	72
Male Participants .....	74
Female Participants .....	74
Discussion .....	79
Male Participants .....	80
Female Participants .....	82
Experiment 2 .....	87
Method .....	88
Participants .....	88
Stimuli .....	88
Procedure .....	89
Results .....	89
Block 1 .....	91
Block 2 .....	91
Discussion .....	94
Experiment 3 .....	98
Method .....	99
Participants .....	99
Stimuli .....	100
Procedure .....	100
Results .....	100
Preliminary Analyses .....	101
Reaction Time and Accuracy .....	101

Normality.....	101
Between Subjects.....	104
Block 1.....	104
Male Participants.....	104
Female Participants.....	105
Block 2.....	106
Male Participants.....	106
Female Participants.....	111
Within Subjects.....	115
Block 1.....	115
Male Participants.....	115
Female Participants.....	116
Block 2.....	118
Male Participants.....	118
Female Participants.....	121
Discussion.....	123
Between Subjects Analysis.....	123
Within Subjects Analysis.....	126
General Discussion.....	129
Comments on Theoretical Findings.....	130
Assumption of Consistency.....	130
Assumption of Inconsistency.....	135
A Priori Hypotheses.....	140
Four-way interaction.....	141
Main effects	
Main effect of task.....	143
Main effect of bin.....	143
Main effect of Frequency.....	144
Summary of findings.....	145
Additional effects	
Sex Differences.....	147
Block Effect.....	148
Critical Questions Remaining.....	148
Comments on the Double Double Dissociation.....	150
Post-Script.....	153
References.....	155

## List of Tables

### Experiment 1

1. All Conditions Organized by Task, Hemisphere, Bin Size and Frequency.....	56
2. Mean Reaction Times from Kosslyn et al. (1989) Compared to Comparable Conditions (Small Bin, High Frequency) in the Present Study.....	63
3. Mean Accuracy Scores (Standard Deviations) for Task x Hemisphere for the Comparable Conditions to Kosslyn et al (1989).....	64
4. Correlation Coefficients for Reaction Time and Accuracy for the Topological Conditions (n = 70 ).....	65
5. Correlation Coefficients for Reaction Time and Accuracy for the Metric Conditions (n = 65).....	66

### Experiment 3

6. Correlation Coefficients for Reaction Time and Accuracy for the Topological Conditions (n = 60).....	102
7. Correlation Coefficients for Reaction Time and Accuracy for the Metric Conditions (n = 60).....	103

## List of Figures

### Experiment 1

1. Hypothesized predictions based on bin theory.....	46
2. Hypothesized predictions based on spatial frequency theory.....	47
3. Predicted test of the assumption of consistency.....	48
4. Predicted test of the assumption of inconsistency.....	49
5. Sequence of presentation for bar and dot stimulus.....	59
6. Sequence of presentation for circle and dot stimulus.....	60
7. Block 1, male participants, a priori hypotheses.....	70
8. Block 1, female participants, a priori hypotheses.....	71
9. Block 1, female participants, test of consistency, large bin, low frequency.....	73
10. Block 2, female participants, a priori hypotheses.....	76
11. Block 2, female participants, test of consistency, large bin, low frequency.....	77
12. Block 2, female participants, test of consistency, small bin, high frequency.....	78

### Experiment 2

13. Block 1, rightward saccades at 100, 117 and 150 ms.....	92
14. Block 1, leftward saccades at 100, 117 and 150 ms.....	93
15. Block 2, rightward saccades at 100, 117 and 150 ms.....	95
16. Block 2, leftward saccades at 100, 117 and 150 ms.....	96

### Experiment 3

17. Between subjects, Block 1, female participants, exposure duration x condition, a priori hypotheses.....	107
--	-----

18. Between subjects, Block 1, female participants, task x bin.....	108
19. Between subjects, Block 1, female participants, hemisphere x frequency.....	109
20. Between subjects, Block 2, male participants, a priori hypotheses.....	110
21. Between subjects, Block 2, male participants, test of inconsistency.....	112
22. Between subjects, Block 2, female participants, a priori hypotheses.....	113
23. Within subjects, Block 1, female participants, a priori hypotheses.....	117
24. Within subjects, Block 2, male participants, task x hemisphere, large bin conditions.....	119
25. Within subjects, Block 2, male participants task x hemisphere, small bin conditions.....	120
26. Within subjects, Block 2, male participants, test of consistency, small bin, high frequency conditions.....	122

## List of Appendices

Appendix A: Ethics Approval, consent form and Debrief form.....	157
Appendix B: Handedness Questionnaire.....	160
Experiment 1	
Appendix C: Pilot Study 1.....	162
i. Circle and Dot stimuli for the First Pilot Study ii. RT, task x hemisphere	
ii. ANOVA Table for the First Pilot Study, Task x Hemisphere, Reaction Time, Central Reference	
iii. ANOVA Table for the First Pilot Study, Task x Hemisphere, Reaction Time, Peripheral Reference	
iv. ANOVA Table for the First Pilot Study, Task x Hemisphere, Accuracy, Central Reference	
v. ANOVA Table for the First Pilot Study, Task x Hemisphere, Accuracy, Peripheral Reference	
vi. Mean Reaction Time (Standard Deviation) and Accuracy (Standard Deviation) Data for the First Pilot for all Variables (n = 10)	
Appendix D Pilot study 2.....	168
i. ANOVA Table for the Second Pilot Study, Task x Hemisphere, Reaction Time	
ii. ANOVA Table for the Second Pilot Study, Task x Hemisphere, Accuracy	
iii. Mean Reaction Time (Standard Deviation) and Accuracy (Standard Deviation) Data for the Second Pilot for all Variables (n = 16)	
Appendix E: Final Pilot Study.....	171
i. Bar and Dot Stimuli for the Final Pilot Study	
ii. ANOVA Table for the Final Pilot Study, Between Groups, Task x Hemisphere, Reaction Time	

iii.	ANOVA Table for the Final Pilot Study, Within Subjects, Task x Hemisphere, Reaction Time	
iv.	ANOVA Table for the Final Pilot Study, Within Subjects, Task x Hemisphere, Reaction Time	
v.	ANOVA Table for the Final Pilot Study, Within Subjects, Task x Hemisphere, Accuracy	
vi.	Mean Reaction Time (Standard Deviation) and Accuracy (Standard Deviation) Data for the Final Pilot, Within Subjects for All Variables (n = 11)	
Appendix F	.....	180
i.	Clear Bar and Dot Stimuli	
ii.	Blurred Bar and Dot Stimuli	
iii.	Clear Circle and Dot Stimuli	
iv.	Blurred Circle and Dot Stimuli	
Appendix G	.....	184
i.	Mean Reaction Time (Standard Deviation) and Accuracy (Standard Deviation) Data for all Variables (n = 65)	
Appendix H	.....	186
i.	Shapiro-Wilks t Statistics for all Variables (df = 55)	
Appendix I	.....	187
i.	ANOVA Table for Transformed Efficiency Scores for Block Effects (Block x Task x Hemisphere x Bin x Frequency)	
ii.	Means and Standard Deviations for Each Variable and Each Block with Significant Between Block Differences Indicated	
Appendix J	.....	191
i.	ANOVA Table for Transformed Efficiency Scores for Sex effects, Block 1 (Sex x Task x Hemisphere x Bin x Frequency)	
ii.	Figure Jii	

iii. Figure Jiii

Appendix K ..... 196

- i. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Hemisphere(Task Consistent) x Condition (Hemispherically Inconsistent)
- ii. Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for Block 1, Male Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)
- iii. ANOVA Table of Transformed Efficiency Scores for Block 1, Male Participants, Task x Hemisphere x Bin x Frequency
- iv. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Task x Hemisphere, Large Bin, High Frequency Conditions
- v. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Task x Hemisphere, Large Bin, Low Frequency Conditions
- vi. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Task x Hemisphere, Small Bin, High Frequency Conditions
- vii. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Task x Hemisphere, Small Bin, Low Frequency Conditions
- viii. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)
- ix. Means and Standard Deviations for Each Variable for Block 1, Male Participants

Appendix L ..... 207

- i. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Inconsistent)
- ii. Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for Block 1, Female Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)
- iii. ANOVA Table of Transformed Efficiency Scores for Block 1, Female

Participants, Task x Hemisphere x Bin x Frequency

- iv. Figure Liv
- v. ANOVA Table of Transformed Efficiency Scores for Block 1, Female Participants, Topological task, Hemisphere x Bin x Frequency
- vi. ANOVA Table of Transformed Efficiency Scores for Block 1, Female Participants, Metric task, Hemisphere x Bin x Frequency
- vii. ANOVA Table of Transformed Efficiency Scores for Block 1, Female Participants, Metric task, Left Hemisphere, Bin x Frequency
- viii. ANOVA Table of Transformed Efficiency Scores for Block 1, Female Participants, Metric task, Left Hemisphere, Bin x Frequency
- ix. Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for Block 1, Female Participants, Metric Task, Right Hemisphere, Bin x Frequency
- x. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Task x Hemisphere, Large Bin, High Frequency Conditions
- xi. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Task x Hemisphere, Large Bin, Low Frequency Conditions
- xii. Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for Block 1, Female Participants, Task x Hemisphere, Large Bin, Low Frequency
- xiii. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Task x Hemisphere, Small Bin, High Frequency Conditions
- xiv. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Task x Hemisphere, Small Bin, Low Frequency Conditions
- xv. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)
- xvi. Means and Standard Deviations for Each Variable for Block 1, Female Participants

- i. ANOVA Table for Transformed Efficiency Scores for Block 2, Sex x Task x Hemisphere x Bin x Frequency
- ii. Figure Mii
- iii. Figure Miii

Appendix N ..... 232

- i. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants, Hemisphere(Task Consistent) x Condition (Hemispherically Inconsistent)
- ii. ANOVA Table of Transformed Efficiency Scores for Block 2, Male Participants, Task x Hemisphere x Bin x Frequency
- iii. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants, Task x Hemisphere, Large Bin, High Frequency Conditions
- iv. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants, Task x Hemisphere, Large Bin, Low Frequency Conditions
- v. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants, Task x Hemisphere, Small Bin, High Frequency Conditions
- vi. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants, Task x Hemisphere, Small Bin, Low Frequency Conditions
- vii. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)

Appendix O ..... 242

- i. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants, Hemisphere(Task Consistent) x Condition (Hemispherically Inconsistent)
- ii. Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for Block 2, Female Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)
- iii. ANOVA Table of Transformed Efficiency Scores for Block 2, Female Participants, Task x Hemisphere x Bin x Frequency
- iv. Figure Oiv

- v. ANOVA Table of Transformed Efficiency Scores for Block 2, Female Participants, Topological task, Hemisphere x Bin x Frequency
- vi. ANOVA Table of Transformed Efficiency Scores for Block 2, Female Participants, Metric task, Hemisphere x Bin x Frequency
- vii. ANOVA Table of Transformed Efficiency Scores for Block 2, Female Participants, Metric task, Left Hemisphere, Bin x Frequency
- viii. Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for Block 2, Female Participants, Metric Task, Left Hemisphere, Bin x Frequency
- ix. ANOVA Table of Transformed Efficiency Scores for Block 2, Female Participants, Metric task, Right Hemisphere, Bin x Frequency
- x. Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for Block 2, Female Participants, Metric Task, Right Hemisphere, Bin x Frequency
- xi. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants, Task x Hemisphere, Large Bin, High Frequency Conditions
- xii. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants, Task x Hemisphere, Large Bin, High Frequency Conditions
- xiii. Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for Block 2, Female Participants, Task x Hemisphere, Large Bin, Low Frequency
- xiv. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants, Task x Hemisphere, Small Bin, High Frequency Conditions
- xv. Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for Block 2, Female Participants, Task x Hemisphere, Small Bin, High Frequency
- xvi. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants, Task x Hemisphere, Small Bin, Low Frequency Conditions
- xvii. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)

- xviii. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)
- xix. Means and Standard Deviations for Each Variable for Block 2, Female Participants

Experiment 2

Appendix P..... 264

- i. ANOVA Table for Mean Difference Scores For Block Effects for Block x Task x Hemisphere x Bin x Frequency x Exposure Duration (Greenhouse-Geisser Correction)
- ii. Significant Differences Between Test Value (93.8) and Distance of Saccadic Movement (Pixels) for Each Block
- iii. Means for Distance of Saccadic Movement (pixels) for Each Block

Experiment 3

Appendix Q..... 271

- i. High and Low Spatial Frequency Masks Used for Experiment 3

Appendix R..... 272

- i. Mean Reaction Time (Standard Deviation) and Accuracy (Standard Deviation) Data for All Variables (n = 60)

Appendix S..... 274

- i. Shapiro-Wilks Statistics for All Variables for Exposure Duration = 100 ms (df = 18)
- ii. Shapiro-Wilks Statistics for All Variables for Exposure Duration = 150 ms (df = 26)

Appendix T..... 276

- i. ANOVA Table of Transformed Efficiency Scores for 5 Within (Block, Task, Hemisphere, Bin, Frequency) and 2 Between (Exposure Duration, Sex) for Block, Exposure Duration and Sex Effects

- ii. Means and Standard Deviations for Each Variable and Each Block With Significant Between Block Differences Indicated

Appendix U ..... 289

- i. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Inconsistent)
- ii. ANOVA Table of Transformed Efficiency Scores for Block 1, Male Participants, Exposure Duration x Task x Hemisphere x Bin x Frequency
- iii. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Task x Hemisphere, Large Bin, High Frequency Conditions
- iv. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Task x Hemisphere, Large Bin, Low Frequency Conditions
- v. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Task x Hemisphere, Small Bin, High Frequency Conditions
- vi. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Task x Hemisphere, Small Bin, Low Frequency Conditions
- vii. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)
- viii. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)
- ix. Means and Standard Deviations for Each Variable for Block 1, Male Participants for the 150 and 100 ms Exposure Duration Groups

Appendix V ..... 306

- i. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Inconsistent)
- ii. ANOVA Table of Transformed Efficiency Scores for Block 1, Female Participants, Exposure Duration x Task x Hemisphere x Bin x Frequency
- iii. Figure Viii

- iv. Figure Viv
- v. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Task x Hemisphere, Large Bin, High Frequency Conditions
- vi. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Task x Hemisphere, Large Bin, Low Frequency Conditions
- vii. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Task x Hemisphere, Small Bin, High Frequency Conditions
- viii. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Task x Hemisphere, Small Bin, Low Frequency Conditions
- ix. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)
- x. Means and Standard Deviations for Each Variable for Block 1, Female Participants for the 150 and 100 ms Exposure Duration Groups

Appendix W ..... 325

- i. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Inconsistent)
- ii. ANOVA Table of Transformed Efficiency Scores for Block 2, Male Participants, Exposure Duration x Task x Hemisphere x Bin x Frequency
- iii. Figure Wiii
- iv. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants, Task x Hemisphere, Large Bin, High Frequency Conditions
- v. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants, Task x Hemisphere, Large Bin, Low Frequency Conditions
- vi. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants, Task x Hemisphere, Small Bin, High Frequency Conditions
- vii. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants, Task x Hemisphere, Small Bin, Low Frequency Conditions
- viii. ANOVA Table for Transformed Efficiency Scores for Block 2, Male

	Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)	
ix.	Means and Standard Deviations for Each Variable for Block 2, Male Participants for the 150 and 100 ms Exposure Duration Groups	
Appendix X	.....	343
i.	ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Inconsistent)	
ii.	ANOVA Table of Transformed Efficiency Scores for Block 2, Female	
iii.	Participants, Exposure Duration x Task x Hemisphere x Bin x Frequency	
iv.	Figure Xiii	
v.	Figure Xiv	
vi.	ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants, Task x Hemisphere, Large Bin, High Frequency Conditions	
vii.	ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants, Task x Hemisphere, Large Bin, Low Frequency Conditions	
viii.	ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants, Task x Hemisphere, Small Bin, High Frequency Conditions	
ix.	ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants, Task x Hemisphere, Small Bin, Low Frequency Conditions	
x.	ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)	
xi.	Means and Standard Deviations for Each Variable for Block 2, Female Participants for the 150 and 100 ms Exposure Duration Groups	
Appendix Y	.....	362
i.	ANOVA Table of Transformed Efficiency Scores for 5 Within (Block, Task, Hemisphere, Bin, Frequency) and 1 Between (Sex) for 100 ms Exposure Duration	
ii.	Means and Standard Deviations for Female Participants at 100 ms for	

Each Variable and Each Block with Significant Between Block Differences Indicated

- iii. Means and Standard Deviations for Male Participants at 100 ms for Each Variable and Each Block with Significant Between Block Differences Indicated

Appendix Z ..... 371

- i. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Hemisphere(Task Consistent) x Condition (Hemispherically Inconsistent)
- ii. ANOVA Table of Transformed Efficiency Scores for Block 1, Male Participants, Task x Hemisphere x Bin x Frequency
- iii. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Task x Hemisphere, Large Bin, High Frequency Conditions
- iv. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Task x Hemisphere, Large Bin, Low Frequency Conditions
- v. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Task x Hemisphere, Small Bin, High Frequency Conditions
- vi. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Task x Hemisphere, Small Bin, Low Frequency Conditions
- vii. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)
- viii. Means and Standard Deviations for Each Variable for Block 1, Male Participants.

Appendix AA ..... 381

- i. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Inconsistent)
- ii. ANOVA Table of Transformed Efficiency Scores for Block 1 Female Participants, Task x Hemisphere x Bin x Frequency

- iii. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Task x Hemisphere, Large Bin, High Frequency Conditions
- iv. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Task x Hemisphere, Large Bin, Low Frequency Conditions
- v. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Task x Hemisphere, Small Bin, High Frequency Conditions
- vi. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Task x Hemisphere, Small Bin, Low Frequency Conditions
- vii. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)
- viii. Means and Standard Deviations for Each Variable for Block 1, Female Participants

Appendix BB ..... 391

- i. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Inconsistent)
- ii. ANOVA Table of Transformed Efficiency Scores for Block 2, Male Participants, Task x Hemisphere x Bin x Frequency
- iii. Figure BBiii
- iv. Figure BBiv
- v. ANOVA Table for Transformed Efficiency Scores for Block 2 Male Participants, Task x Hemisphere, Large Bin, High Frequency Conditions
- vi. ANOVA Table for Transformed Efficiency Scores for Block 2 Male Participants, Task x Hemisphere, Large Bin, Low Frequency Conditions
- vii. ANOVA Table for Transformed Efficiency Scores for Block 2 Male Participants, Task x Hemisphere, Small Bin, High Frequency Conditions
- viii. ANOVA Table for Transformed Efficiency Scores for Block 2 Male Participants, Task x Hemisphere, Small Bin, Low Frequency Conditions
- ix. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)

- x. Means and Standard Deviations for Each Variable for Block 2, Male Participants

Appendix CC ..... 403

- i. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Inconsistent)
- ii. ANOVA Table of Transformed Efficiency Scores for Block 2, Female Participants, Task x Hemisphere x Bin x Frequency
- iii. ANOVA Table for Transformed Efficiency Scores for Block 2 Female Participants, Task x Hemisphere, Large Bin, High Frequency Conditions
- iv. ANOVA Table for Transformed Efficiency Scores for Block 2 Female Participants, Task x Hemisphere, Large Bin, Low Frequency Conditions
- v. ANOVA Table for Transformed Efficiency Scores for Block 2 Female Participants, Task x Hemisphere, Small Bin, High Frequency Conditions
- vi. ANOVA Table for Transformed Efficiency Scores for Block 2 Female Participants, Task x Hemisphere, Small Bin, Low Frequency Conditions
- vii. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)
- viii. Means and Standard Deviations for Each Variable for Block 2, Female Participants

## Preface

The most serious challenge in scientific investigation, I think, must be to forfeit the easy answer for the possibilities. A true testament to a researcher's talent lies in the ability to overcome the quest for the solution in favor of the search for the next problem. And so, with great respect, I read the work of Dr. Stephen Kosslyn and the late Dr. Justine Sergent both of whom, through their work, have demonstrated an intellectual and personal capacity to hear the other side. In this paper, I try to engage the challenges they have inspired.

Perhaps visual perception, in its broadest application, is the best, certainly it is not the least, understood of all brain functions. Having enjoyed a rich empirical history, discovery has been both methodical and serendipitous, consistent and contrary, and has become even more interesting by its close association to processes that have come to be included under the general rubric of "attention". "One of the most extraordinary facts of our life," wrote William James (1892, p. 217), "is that, although we are besieged at every moment by impressions from our whole sensory surface, we notice so very small a part of them." Indeed, we are confronted daily with the riddles of visual attention. For example, how does my brain know that I have passed my freeway exit the moment I pass it? How can I "read" to the end of a page of text and suddenly, upon turning it, realize that I have not comprehended a thing? Why am I only able to see falling stars out of my periphery and when I shift my eyes to look at them, they seem to disappear? Each question conjures a voluminous literature. Although early examinations were limited to

asking these questions in terms of perception or attention, recent work has begun to broach the two fields, finding new associations between them.

In the spirit of common ground, this work seeks the interface between perception, attention and high-level visual processes. While the empirical paradigm pits theory against theory, I do not intend to conclude that Kosslyn or Sergent were either right or wrong. To do so would violate the constructive spirit of their academic exchanges. Indeed, both have respectfully reformulated their thinking in keeping with the challenges raised by the other. I hope that I can take up these challenges that have necessarily gone unanswered with the same intention; that is, to further the current direction, inspire future questions and seek new problems.

ASYMMETRY IN SPATIAL JUDGMENTS:  
TESTING BIN THEORY AND SPATIAL FREQUENCY THEORY  
IN A DOUBLE DOUBLE DISSOCIATION DESIGN

OVERVIEW

Diametric descriptions of high-level hemispheric asymmetries are many, parsimonious explanations unfortunately few. This paper attempts to address this paucity by examining hemispheric asymmetries of high-level visual processes at a more fundamental level, the level of stimulus input and by demonstrating a method for dissociating asymmetrically distributed input characteristics using asymmetrically distributed tasks. The input characteristics being examined here are attended receptive field and spatial frequency of the stimulus. Bin theory of spatial attention posits asymmetrical processing on the basis of stimulus size (Chabris & Kosslyn, 1998; Kosslyn, Chabris, Marsolek & Koenig, 1992) and spatial frequency theory posits asymmetrical processing on the basis of spatial frequency (Sergent, 1982a). The asymmetrically distributed tasks being tested here are two high level spatial judgment tasks. Utilizing a new design, this study will attempt to determine whether attentional bin size or spatial frequency of the stimulus is the primary constraining factor in high level spatial judgments.

The work of Kosslyn and his colleagues likely represents one of the most comprehensive bodies of work on high-level spatial judgments. His well-reasoned model supports two fundamental processes, a topological one and a metric one, and incorporates attentional and executive control features. He and others have generally found that the right hemisphere seems better able to perform metric tasks, and the left

hemisphere seems better able to perform topological tasks (Cowin & Hellige, 1994; Hellige, Bloch, Cowin, Eng, Eviatar & Sergent, 1994; Hellige & Michimata, 1989; Kosslyn, Koenig et al. 1989; Laeng & Peters, 1995; Rybash & Hoyer, 1992; see Jager & Postma, 2003, for a review). These findings suggest that the right hemisphere superimposes a hypothetical metric grid on the visual scene that enables one to assess distances whereas the left hemisphere is more adept at forming categories to describe relationships among objects or parts of objects. However, these findings have been difficult to replicate with even small variations in stimuli or procedure implying that the effect is specifically associated with task demands and not sufficiently robust to constitute evidence of a genuine hemispheric asymmetry (Bruyer, Scailquin, & Coibion 1997; Sergent, 1991).

Perhaps, the heartiest criticism of Kosslyn's two-process model has come from one of the strongest proponents of spatial frequency theory, Dr. Justine Sergent. Spatial frequency theory holds that the right hemisphere is specialized for processing low spatial frequencies and the left hemisphere is specialized for processing high spatial frequencies. Sergent (1991) showed that the asymmetrical two-process effect was dependent upon the luminance level of the screen and therefore the spatial frequencies at which the stimuli were presented. Kosslyn's weighty reply to these criticisms rendered an unexpected finding which ultimately led to a reformulation of his model. The reformulation included an attentional mechanism that effectively parsed the visual fields into small and large regions or "bins" of processing space. These bins are assumed to be the attentional analogue of retinal receptive fields (Chabris & Kosslyn, 1998; Kosslyn, Chabris, Marsolek & Koenig, 1992).

Bin theory, as I have termed it here, posits that the left hemisphere is more efficient at processing input from relatively smaller bins or receptive fields while the right hemisphere is more efficient at processing input from relatively larger bins or receptive fields. These attentional properties are regulated by the task demands which are differentially served by each hemisphere. In other words, when the task demands metric judgment, particular attentional faculties, the large bins, are utilized to facilitate such a judgment. Likewise, when the task requires an assessment of topological relationships, small bins are utilized to facilitate such an assessment (Chabris & Kosslyn, 1998). Others, more recently, have shown that when the stimuli typically used in these tasks are interpreted according to the spatial frequency by which each hemisphere “sees” them, the results could be predicted simply on the grounds of the difficulty that the task poses for each hemisphere (Ivry & Robertson, 1998).

So far then, two potential explanations for asymmetrical spatial judgments have been suggested. First, as Kosslyn and colleagues suggested, the effect might be mediated by asymmetrical attentional bins, the right hemisphere mediating input from large attentional bins and the left from small attentional bins. If the task is best performed using large bins, the right hemisphere will show a performance advantage, but if the task is best performed using small bins, the left hemisphere will show a performance advantage. Second, the effect might simply be an artifact of asymmetrical processing of spatial frequencies; if the task is performed more easily under low spatial frequency conditions, the right hemisphere will manifest the advantage, but if the task is performed more easily under high frequency conditions, the left hemisphere will manifest a performance advantage. A third and more complicated possibility is that asymmetrical

effects in high-level visual processing might be multiply determined by both bin and frequency. The shape of this relationship might reflect an asymmetrical dependent relationship between bin and frequency or it might reflect an asymmetrical task dependent relationship between bin and frequency. Speculation about the dependent relationship between bin size and spatial frequency derives from Fourier analysis showing a higher proportion of low spatial frequencies in large stimuli and a higher proportion of high spatial frequencies in small stimuli. The left hemisphere is believed to have the advantage when processing input through small receptive fields and when stimuli contain a larger proportion of high spatial frequencies whereas the right hemisphere is believed to have the advantage when processing input through large receptive fields and when stimuli contain a larger proportion of low spatial frequencies (Kosslyn, Anderson, Hilliger & Hamilton, 1992: Kosslyn, Chabris et al., 1992).

Whether the hemispheres process bin size or spatial frequency has been a question for academic exchange but has not been effectively tested using these tasks. Moreover, that the relationship between the size of an attended area and spatial frequency might change depending upon the requirements of a task has not been previously considered. Rather, performance of the tasks has been attributed to large bin sizes (Kosslyn, Anderson et al., 1992) or to low spatial frequencies (Ivry & Robertson, 1998) without consideration for the possibility of task dependent interaction between these input characteristics.

Complications aside, what is apparent in these alternative explanations is that, for the most part, they differ critically in the nature of the input being utilized by the high-level visual mechanisms. According to Kosslyn and colleagues input into high-level visual processes is determined by area; the visual array is parsed into small and

large regions of space by an attentional mechanism. Proponents of spatial frequency, however, hold that input into high-level visual processes is determined not by area but by spatial frequency. The purpose of this thesis is to determine whether the size of the attentional bin or the spatial frequency of the stimulus are critical in the performance of metric and topological tasks. In making this determination a design, the double double dissociation, is developed to test two asymmetrical predictions about input characteristics against each other using asymmetrically distributed tasks. This design will be elaborated later in the paper.

### The Evolution of a Percept

Take a moment to look out a window. Examine the various characteristics of the picture you see. Perhaps a car is consuming much of your focus, a shrub behind it with small blossoms on it casting a shadow across the flat driveway which is dappled in shimmering light as the breeze blows through the leaves. In your periphery, you might detect the window sill, the curtain and perhaps even in the far periphery, pictures on the walls, the soft contours of a couch, your coffee cup.

But what you really “see” is the amalgamation of a complex set of interacting features detected by your visual system. The objects have hard edges and soft edges, colours, variations in lightness and opaqueness, contrast, shadows, textures and movement. The objects have shape and size. The tire of the car is round and large, the blossoms small and star-shaped. We are also able to locate not only the objects but to recognize the various component parts of each object. We know that the hubcap is part of the wheel, the windshield part of the car and that the blossoms are not suspended in front of the shrub but are, in fact, connected to it. Furthermore, without any intentional

computations, we are able to assess relative locations, so we know that the window is closer to us than the car. The images that we see vary in multiple dimensions; each feature is qualitatively distinct. However, the eye, as far as we know, is not designed to differentiate between these features. Rather, as these features enter the eye, they are little more than a pattern of light reflected from the scene. The information activating the retina is only a compilation of light waves varying in size of the retinal receptive field activated and in frequency, with each frequency varying only in amplitude and phase. From here, the job of the visual system is to process all input and delicately distinguish frequencies, respond selectively and reconstruct the scene for interpretation by higher cognitive mechanisms.

In more scientific terms, the visual system analyses and synthesizes the incoming spatial frequency in a physiological reflection of Fourier's theorem. Fourier's theorem for vision states that what we see is mathematically described as the sum of sine waves of different frequencies with each frequency having a particular amplitude and phase (Weisstein, 1980). Frequency is the number of times the sine wave repeats (the number of cycles) over a given amount of space usually degrees visual angle (the number of degrees subtended by an object when it is projected onto the retina). Low frequency sine waves represent few cycles per visual angle, and high frequency sine waves represent many cycles per visual angle. Phase is defined as the point at which the cycle begins, whether the cycle begins at a point of high or low intensity. Amplitude represents the height of the wave. Fourier analysis simply describes the deconstruction of frequencies into a fundamental wave and a series of harmonics with smaller

amplitudes. Fourier synthesis describes the summation of the fundamental and harmonic waves to equal the sine wave (Goldstein, 1996; Weisstein, 1980).

Physiologically, in the visual cortex, certain receptive fields are not only tuned to respond to certain orientations (Moran & Desimone, 1985), but they also respond selectively to certain spatial frequencies (Campbell & Robson, 1968; De Valois, Albrecht & Thorell, 1982). The compilation of the various neurons firing in response to various orientations and frequencies represents the cortical response to the collection of sine waves presented in the retinal image. Weisstein (1980) theorizes that where the phase of a frequency matches the point of highest sensitivity within a receptive field, an additive function occurs resulting in the firing of the neuron most sensitive to that frequency. Where a peak phase coincides with an insensitive region of a receptive field, inhibition occurs. The resulting neural image of the stimulus is then a retinotopic mapping of activation with adjacent inhibition.

Although Weisstein's (1980) suggestion holds well in cases where a simple stimulus is projected to the visual cortex, her theory tells only half the story in cases where the image is complex as are most images that we see. Recall, the description of the images that are received by the cortex through the ordinary act of looking out the window. Fourier analysis of such an image would be astounding and might well overload a relatively simple response mechanism like the retina. Furthermore, for all parts of the image beyond the object of interest, Fourier decomposition could be considered redundant and an inefficient means of processing visual input. Fortunately, the system has adapted a means of selecting only parts of the image and thereby limiting the neural response (Davis & Graham, 1981; Moran & Desimone, 1985).

The nature of this selection process is the question being put to the double double dissociation method, specifically whether the parts of the visual scene are selected for task relevant bin sizes or task relevant frequencies. Before proceeding however, a preliminary discussion of the relevant theories and the development of the method will be described. Spatial frequency theory will be discussed first with reference to the associations between input characteristics that are relevant to visual half field studies. Next, the development of two-process theory will be reviewed. Third, bin theory will be presented and supporting evidence will be described. Finally, the double double dissociation method will be explained for the purpose of providing a rationale for the specific hypotheses presented.

### Spatial Frequency Theory

Spatial frequency theory posits that the performance of high-level cognitive processes mediated by the right hemisphere is influenced predominantly by neurons responsive to low frequency information whereas performance of high-level cognitive processes mediated by the left hemisphere is influenced predominantly by neurons responsive to high frequency information (Sergent, 1982a). Recent modifications to the theory include the concept of relativity; that is, the right hemisphere utilizes input from the relatively lower frequency pathways whereas the left hemisphere utilizes input from the relatively higher frequency pathways (Christman, Kitterle & Hellige, 1991; Ivry & Robertson, 1998). Evidently, the asymmetrical utilization of these frequencies occurs beyond the primary perceptual processes as has been shown by the lack of asymmetry in detection tasks but the presence of asymmetry in identification and other more cognitively taxing tasks (Kitterle, Christman & Hellige, 1990; Kitterle, Hellige &

Christman, 1992). According to spatial frequency theory then, processing efficiency is a combined function of the high-level utilization of the relative proportions of spatial frequencies inherent in the stimulus and of the frequency information needed to complete a given task.

Impressively, spatial frequency theory can reconcile a number of influential hemispheric dichotomies. For example, spatial frequency theory with its recent modifications can account for the global precedence effect. The global precedence effect describes the phenomenon in which large letters composed of smaller letters are identified more quickly than the small letters (Navon, 1977). Spatial frequency theory predicts asymmetrical effects because the global letters, being larger and more degraded, necessarily are lower in frequency than local letters, being smaller and clearer and therefore higher in frequency. Consistent with spatial frequency theory, when presented tachistoscopically, lateral differences emerge. When the large letters are the targets and the small letters are not, reaction times are significantly faster when the stimulus is presented in the left visual field indicating a right hemisphere advantage, but when the small letters are targets and the large letters are not, reaction times are significantly faster when the stimulus is presented in the right visual field indicating a left hemisphere advantage (Badcock, Whitworth & Badcock, 1990; Sergent, 1982a; Shulman, Sullivan, Gish & Sakoda, 1986).

Spatial frequency theory can also reconcile hemispheric differences in verbal and visuospatial processing because verbal and visuospatial tasks are qualitatively different and utilize different frequency information. Verbal tasks, such as reading, typically involve familiar and over-learned stimuli from a finite set of exemplars where every

feature of the stimulus is needed for processing, so high spatial frequency information is critical to successful performance of the typical verbal task. Visuospatial tasks, on the other hand, usually involve an infinite set of shapes and subtend a larger degree of visual angle, so successful completion of a visual task can be accomplished using low spatial frequency information (Sergent, 1982a). Furthermore, very different higher level processes are often required of verbal and visuospatial tasks. Verbal tasks frequently require identification which necessitates high frequency information whereas visuospatial tasks frequently require same/different judgments which do not rely necessarily on high frequency information (Sergent, 1982a).

Spatial frequency theory is also consistent with the general concept of microgenesis of perception. Microgenesis holds that the representation of a percept is not an immediate event. Rather, the percept develops over time. In the initial stages of development, the percept is incomplete, degraded and undifferentiated. Over time, the percept gains clarity, inner details and configural qualities (Flavell & Draguns, 1957; Vassilev & Mitov, 1976; Mihaylova, Stomonyakov & Vassilev, 1999). The gross features are discriminable early in processing but time in the order of several hundred milliseconds is required before the energy of a stimulus has summated to a degree sufficient for the depiction of finer details (Eriksen & Schultz, 1977). Consistent with this, spatial frequency theory predicts that the right hemisphere, being tuned for lower frequency information, can process the stimulus without clarity and details and therefore sooner than the left hemisphere, but the left hemisphere, requiring higher frequency information, must wait until the input has accumulated enough clarity and detail before responding (Sergent, 1983a).

Much support for spatial frequency theory can be found from investigations of the effects of stimulus characteristics and procedure. The majority of this work supports the claim that the right hemisphere has a relative advantage when it comes to processing low frequency information. However, a number of variables that alter spatial frequency of the input can impact this advantage under visual half field presentation. Procedural variables will be presented first followed by specific stimulus characteristics. Procedural variables include exposure duration and retinal eccentricity, and stimulus characteristics include contrast, luminance and resolution. Furthermore, observed relationships among these variables have led to speculation about the over determination of asymmetrical high level cognitive processes. In other words, no one variable accounts for hemispheric advantages, but rather the associations between these variables contribute to asymmetrical performance.

#### *Procedural Variables*

##### *Exposure duration.*

Exposure duration influences the spatial frequencies available for processing and has been shown to affect hemispheric asymmetries (Bradshaw, Hicks & Rose, 1979; Pring, 1981; Sergent, 1982b, 1983b, 1987). Consistent with microgenesis, the right hemisphere appears to be more adept at processing the early available, still degraded stimulus (low spatial frequency) information with the advantage persisting to a duration of about 120 ms. At this point, the advantage seems to switch to the left hemisphere which is more adept at discerning the higher frequencies that define details of an image. This effect persists even when stimulus energy is held constant across long and short durations by manipulating luminance (Sergent, 1982b).

The right hemisphere advantage for early available information suggests that the right hemisphere can begin processing sooner than the left hemisphere. On the other hand, because the left hemisphere requires higher frequency information, it must wait for summation beyond a higher critical duration which means it will process input more slowly than the right hemisphere (Sergent, 1987). Wilkinson and Donnelly (1999) examined the effect of exposure duration on the metric and topological tasks used by Kosslyn et al. (1989) and found that the right hemisphere advantage for the metric task emerged only at 100 ms exposure duration not at 200 ms exposure duration (and only using a black-on-white display with stimulus luminance set at  $90 \text{ cd/m}^2$  and background luminance at  $4 \text{ cd/m}^2$ ). This lends considerable credence to the idea that the right hemisphere is able to process earlier available input than the left.

Although these findings quite consistently point to a right hemisphere advantage in processing relatively early available spatial information, the left hemisphere has been shown by some to have a temporal processing advantage (Nicholls & Cooper, 1991; Nicholls & Atkinson, 1993). Reconciling these findings is difficult, but several key differences between these lines of research can be identified. First, the inspection time task employed by Nicholls and colleagues involved identifying which leg of a three sided pi figure was shorter. This task could be accomplished by utilizing early available degraded information, late available higher frequency information or no frequency information at all. The task could have been completed by simply noting the absence of a line in a particular area of the screen. In this sense, the strategy could have been to press one key for the absence of the line and another for the presence of a line regardless of the length of the adjacent side of the box. Along the same lines, consistent with the

proposed categorical functions of the left hemisphere, the task, being essentially a forced binary choice, might have simply required the categorization of a target line as “present” or “absent”. Second, the instructions employed in Nicholls and colleagues’ work emphasized accuracy rather than speed. In fact, response latency was not analyzed. This raises the possibility that the left hemisphere might simply be more accurate than the right hemisphere for this task, a contention that does not challenge a right hemisphere advantage for early available information. Alternatively, participants might have been able to wait for high frequency information thus facilitating a left hemisphere advantage. Third, the right hemisphere might have had a distinct disadvantage in the task because the stimuli were presented under high luminance conditions. Lastly, the mask employed to prevent iconic perceptual traces might have differentially disrupted low frequency information thereby disabling the right hemisphere and producing an apparent left hemisphere advantage. Despite these criticisms, the results produced by Nicholls and colleagues could have important theoretical consequences and should not be discounted.

*Retinal eccentricity.*

Like exposure duration, retinal eccentricity, also influences spatial frequency and impacts on hemispheric asymmetry in processing. Retinal eccentricity is the degree of visual angle from central fixation at which a stimulus is presented. Zero degrees eccentricity represents presentation in central vision. As the degree of visual angle increases, the stimuli are projected to increasingly peripheral regions of the retina where photoreceptors are predominately rods and receptive fields comparatively large. These rod dominated receptive fields are less able to process high spatial frequency and with the decrease in high spatial frequency input into higher level visual cortex, the left

hemisphere evidences greater disruption in processing than the right hemisphere (Sergent, 1983b).

In addition to procedural variables like exposure duration and retinal eccentricity, the characteristics of the stimulus itself can have a powerful impact on the efficiency with which each hemisphere processes. Relevant to the present study are contrast, luminance and resolution.

### *Stimulus Characteristics*

#### *Contrast.*

The relationship between contrast and spatial frequency has been well established. Essentially, by plotting spatial frequency against the point at which gratings are just noticeably different from the background, an inverted U function is created. This contrast sensitivity function (CSF) shows that at very low (about .5 to about 2 c/deg) and high (more than about 10 c/deg) spatial frequencies contrast sensitivity is relatively poor, but between about 2 and 8 c/deg (peak at about 5 c/deg) contrast sensitivity is much better (De Valois, Albrecht et al., 1982; De Valois, Morgan & Snodderly, 1973; Pasternak & Merigan, 1981). Thought of in a different way, a stimulus of low or high spatial frequency must be presented at a higher level of contrast in order for it to be even detected let alone interpreted.

The implication of the CSF with respect to tests of spatial frequency is important. For example, consider a typical spatial frequency test where the low frequency stimuli are presented at about 5 c/deg. and the high frequency stimuli are presented at over 10 c/deg. At 5 c/deg., CSF is high, so reaction time is faster, but over 10 c/deg., CSF is relatively poor so reaction time is slower. Without considering the effect of contrast, one

could conclude that reaction times are faster to low frequency information than high. In terms of hemispheric asymmetry, the right hemisphere might be perceived as responding to low spatial frequency information when it might be as plausibly responding to high contrast sensitivity (Sergent, 1984) or perhaps the left hemisphere is less sensitive to contrast.

*Luminance.*

The association between luminance and spatial frequency is both mathematically and empirically supported. The luminance pathways in the visual system are dominated by magnocellular projections originating with the rods lining the periphery of the retina. Neurons in the magnocellular fields are not only sensitive to low luminance but to low contrast as well. These cells might also be selectively sensitive to lower spatial frequencies (Plainis & Murray, 2000). Under conditions of low luminance, the point spread function (PSF) or the blurring of a point of light as it passes through the lens of the eye is high, making resolution of higher frequencies more difficult and leading to the prediction that the left hemisphere would be disadvantaged in comparison to the right when luminance is low (De Valois, Morgan & Snodderly, 1990). Importantly, this prediction has been supported using metric and topological tasks.

Consistent with previous findings (Christman, 1990), Sergent (1991) found that under conditions of high luminance ( $87 \text{ cd/m}^2$ ), an asymmetrical effect for these tasks could not be obtained, but when topological and metric judgments were required under conditions of low luminance ( $4 \text{ cd/m}^2$ ), a qualitatively similar effect was obtained; that is, performance of the right hemisphere in metric judgments was better than performance of the left hemisphere. Similarly, in face recognition, a significant visual field by

luminance interaction has been found but the effect was due to improved performance of the left hemisphere under conditions of high luminance (Sergent, 1982c). Importantly, luminance was manipulated in both these studies by changing the brightness of the screen including the image projected onto it. Manipulating luminance in this way also implicates contrast as a potentially confounding variable.

The relationships among spatial frequency, contrast and luminance are complicated. In general, the lower the luminance, the lower the spatial frequency and the greater the effect on reaction time of small decreases in contrast. For example, Plainis & Murray (2000) found that at very low levels of luminance ( $.02 \text{ cd/m}^2$  and  $.005 \text{ cd/m}^2$ ) and low spatial frequency ( $.94 \text{ c/deg}$ ), small decreases in contrast increased reaction times dramatically, but at high frequencies ( $11.22 \text{ c/deg}$ ), the effect of variations in luminance on contrast sensitivity was attenuated. Similar findings have been previously reported (De Valois et al., 1974). Bearing in mind that this was merely a detection task and barely taxed the higher cognitive faculties and that no effort was made to consider possible asymmetrical effects in contrast sensitivity functions, the complexity of the relationships examined by these studies is appreciated.

#### *Resolution.*

Two methods are typically used to vary resolution, blurring and altering the size of the stimulus. Blurring the stimulus increases the proportion of low frequencies inherent in the stimulus. When low frequencies are increased by blurring, the right hemisphere shows little change in its ability to make same/different judgments about the stimulus but the left hemisphere shows considerable attenuation in performance (Christman, 1990; Michimata & Hellige, 1987; Jonsson & Hellige, 1986). These results

show that the right hemisphere is adept at processing high and low spatial frequency input whereas the left hemisphere is disadvantaged by low spatial frequency input.

A second way of altering resolution is to vary the size of the stimulus. The effect of stimulus size on lateralized reaction times remains an open question (Michimata & Hellige, 1987; Sergent, 1983b). The difficulty in predicting this effect stems from contrary predictions. Increasing the size of a stimulus, within reason, increases perceptibility (Sergent & Hellige, 1986). If the left hemisphere shows deterioration in performance under degraded stimulus conditions, one could predict that by increasing the size and therefore perceptibility of the stimulus, the left hemisphere would not show such deterioration. This effect appears to be mitigated by the type of judgment required in the task with “same” judgments showing no visual field effects but “different” judgments showing significant effects (Michimata & Hellige, 1987; Taylor & Hellige, 1987). However, by increasing stimulus size, the proportion of low spatial frequencies is also increased predicting a right hemisphere advantage as was found by Sergent (1983b). However, this effect was mitigated by retinal eccentricity with the right hemisphere advantage for large sized stimuli evident only when stimuli appeared in the periphery.

With little analytical wrangling, relationships among resolution, exposure duration and eccentricity emerge. The issue, in any case, is the quality of the information projected to the retina and beyond to high-level visual cortex. Sergent (1983b) noted that neither duration, eccentricity nor stimulus size was sufficient to create asymmetrical responses. Rather, a combination of at least two of the variables was needed before differential hemispheric processing was found. This has been a consistent finding

throughout Sergent's work leading her to state repeatedly that visual perception is over determined by combinations of input characteristics.

In summary, although the spatial frequency of a stimulus is related to many input characteristics including exposure duration, retinal eccentricity, contrast, luminance and resolution, the generally consistent finding is that when input characteristics combine to create low frequency input, the right hemisphere appears to have an advantage over the left. This finding serves as the cornerstone for spatial frequency theory. The appeal of spatial frequency theory lies in its breadth of explanation providing an account of a number of consistently observed phenomena including microgenesis of perception, left hemisphere advantage for verbal stimuli and the global precedence effect.

The most recent variation of spatial frequency theory, double filtering by frequency theory (DFF; Ivry & Robertson, 1998), has introduced the concepts of relativity, selective attention and dual pass filtering mechanisms. This theory is based on the observed need to represent information at multiple scales and to select subsets of that information. In the initial stage of processing, equivalence in sensory input across the hemispheres is assumed. The first filtering stage of DFF represents the operation of a selective attention mechanism that determines which frequencies in the spatial array will be amplified and which will be attenuated. This process is constrained by the spatial frequency properties of the object and by task demands which might make either high or low spatial frequencies more salient. At the second filtering stage, information selected at the first stage undergoes different filtering by each hemisphere. The right hemisphere acts as a low-pass filter amplifying low frequencies while attenuating high frequencies whereas the left hemisphere acts as a high-pass filter amplifying high frequencies while

attenuating low frequencies. At this stage, relatively low spatial frequencies will be filtered out for processing by the right hemisphere whereas relatively high spatial frequencies will be filtered out by the left hemisphere. Effectively, relativity produces a sliding scale of spatial frequency processing such that regardless of the spatial frequencies inherent within, both hemispheres will operate in the processing of the stimulus. Differential filtering between the hemispheres of relative frequencies is a requirement of higher order analyses and decision making (Ivry & Robertson, 1998). DFF represents an important development for spatial frequency theory with the inclusion of the first filtering stage which accounts for the contribution of selective attention to the process of high-level visual processing. This first filter is remarkably like Kosslyn's attentional bins, as will be seen subsequently in this paper. Kosslyn's attentional bins are also hypothesized to select information for further processing in high-level visual structures.

Critical evidence in formulating spatial frequency theory and its successor, DFF, has been presented. The theory derives from the microgenesis of the percept which suggests that visual information is summated across time so that the first features extracted will be degraded and the last features extracted will be detailed. At some level beyond simple detection, the hemispheres have been shown to process early and late information differently with the right hemisphere better able to process early degraded information whereas the left hemisphere must wait until the percept is more clearly delineated. Additional research on retinal eccentricity and stimulus characteristics such as contrast, luminance and resolution was reviewed and found to support asymmetrical processing of spatial frequencies.

## Two-Process Theory of High-Level Visual Processing

Two fundamental processes in high-level vision have been suggested (Kosslyn, 1987; Kosslyn et al., 1989). One process is topological in nature and allows for the identification of relationships between objects or component parts of objects. The other process is metric in character and governs the judgment of absolute distances in egocentric and allocentric space (Kosslyn, 1987; Kosslyn et al., 1989). These processes are believed to be engaged at a level beyond V4 (Kosslyn, Flynn, Amsterdam & Wang, 1990). Although initial replications were convincing, changes in procedure and stimulus characteristics have shown the effect to possess fragility that some have argued casts doubt upon its veridicality (Bruyer, Scailquin & Coibion, 1997; Sergent, 1991). In fact, the effect from which the theory is derived might better be accounted for by spatial frequency theory (Ivry & Robertson, 1998; Sergent, 1991). In this section of the paper, support for the two-process model of high-level visual processing will be reviewed.

The strength of the two-process theory of high-level visual processing lies in its development. At the outset, the theory was constrained in three-ways. First, it had to be capable of explaining how the normal high-level visual system works and how it integrates with low-level visual and other systems. Second, the theory had to be consistent with neuroanatomical and neurophysiological evidence. Third, it had to be capable of explaining the functional performance of the system. In other words, the theory had to account for the tasks that are observed output of the system. In the case of high-level vision, the system had to be able to identify objects seen at different visual angles (size constancy), in different shapes or contortions (shape constancy) and under different input conditions such as clear or impoverished.

The two-process theory of high-level visual processing stems from the discovery of separate pathways for object identification and spatial location also known respectively as the inferior temporal pathway or “what” system and the parietal pathway or “where” system (Ungerleider & Mishkin, 1982). However, in considering the tasks that the visual system must perform, three difficulties are associated with separate object identification and location systems. The first difficulty with having separate processing systems for object identification and location is that in order to identify an object, information about the spatial location of the features of the object is necessary. A second difficulty with having two separate processing systems is how the “what” and “where” systems can recognize a virtually infinite number of representations of objects (Kosslyn, 1987). However, with modifications to the “what” and “where” system theory, these difficulties were addressed.

To address these two problems, the “where” system was deemed to not only locate whole objects in space but to locate component parts of objects and recognize the topological relations between those parts (Kosslyn, 1987). Topological relations define relationships between the component parts of visual input. Take, for example, the human elbow. It could be at any point within a certain radius of the body. When converted into visual input, this information is not helpful to the visual system in its task of identification because other objects could easily fall into this radius. However, the invariant spatial relation between the elbow and shoulder is “connected to”. The elbow is (under ordinary circumstances, at least) connected to the shoulder. This knowledge represents the input from associative memory. If it is the case then that the visual input consists of an unidentified object and a shoulder and the spatial modifier “connected to”,

identification of the object as an elbow is most likely. For this reason, a system that identifies the topological relationships between component parts is needed.

A third difficulty with having separate “what” and “where” systems is how the “what” and “where” systems recognize familiar objects. It is sometimes not enough to know simply the topological relations among component parts because these relations would be the same across many objects of an equivalent class. For example, knowing that your child’s eyes are above his nose does not help you to recognize your child from a classroom full of children. You need to know the precise distance between your child’s nose and eyes in order to recognize him or her. In some circumstances, then, it is important to know precise distances between the parts. A subsystem for assessing metric distances would be useful for this task as well as for navigating through space providing information about the precise distances in egocentric and allocentric space (Kosslyn, 1987).

In summary, then, two modifications to the “where” system were proposed. The first modification was the inclusion of a subsystem that could locate object parts and recognize topological relations between them. Because of this subsystem’s close association with language, the likely hemisphere for mediating this subsystem was thought to be the left. The second modification was the inclusion of a subsystem to assess metric distances. Because of this subsystem’s close association with navigation, the likely hemisphere for mediating this subsystem was thought to be the right (Kosslyn, 1987).

The two-process theory of high-level visual processing has received a measure of support. Using a between groups design, Kosslyn et al. (1989) found a left hemisphere

advantage for topological tasks and a right hemisphere advantage for metric tasks using three different stimuli. First, they found that the left hemisphere was better at identifying when a dot was on or off a random blob and the right hemisphere was better at determining whether the dot was near or far from the random blob. Second, they found a left hemisphere advantage for deciding if a plus sign was to the left or right of a minus sign and a right hemisphere advantage for deciding if the plus and minus sign were more than 1 inch apart. Lastly, they found that the left hemisphere could more quickly identify if a dot was above or below a line and the right hemisphere could more quickly identify if the dot was more or less than 3 mm from a bar. Michimata and Hellige (1989) found a similar advantage. Although the results of PET studies were not conclusive (Kosslyn, Thompson, Gitelman & Alpert, 1998), functional MRI has recently shown a right hemisphere advantage for coordinate tasks and a left hemisphere advantage for categorical tasks (Trojano et al., 2002).

Although task x hemisphere interactions are often found, hemisphere differences in the topological task are usually marginal at best. Compared to the left hemisphere, the right hemisphere appears to be faster when making metric judgments whereas the left hemisphere compared to the right is only marginally faster when making topological judgments (Cowin & Hellige, 1994; Hellige & Michimata, 1989; Kosslyn et al., 1989; Rybash & Hoyer, 1992). Only a few studies report a clear left hemisphere advantage for relational judgments (Laeng, Shah & Kosslyn, 1999). A strict interpretation of this collection of findings would be that the right hemisphere performs distance spatial relations tasks better than the left, but no comment could be made about the performance

of the left hemisphere. Essentially, the two-process theory of high-level visual processing could be considered a theory of the right hemisphere.

Additionally, Kosslyn et al.'s (1989) results have been notoriously difficult to replicate. Kosslyn et al. themselves had difficulty replicating their findings noting in a footnote that they were unable to replicate the results of one of their tasks on a new computer with four subsequent attempts rendering only mixed results. They subsequently found that they could only replicate their results on this task using back-projected slides. For another task, they were only able to replicate their results using a high resolution computer screen with a contrast enhancing Polaroid filter. The effect might well be limited to conditions of low luminance (Kosslyn, et al. 1992, Experiment 4; Sergent, 1991) with a right hemisphere advantage emerging for the metric task arguably because under low luminance, the left hemisphere is compromised but the right hemisphere is not.

Other variations in protocol have also been shown to vary the effect. Procedural variables such as exposure duration, response type and number of decision choices, feedback and interactions between these variables can eliminate the effect for either response latency or error data or both (Bruyer et al., 1997; Wilkinson & Donnelly, 1999). Aging has also been shown to differentially affect performance with increased response latencies for metric tasks performed by participants between 60 and 79 years of age (Bruyer et al., 1997). Although rarely examined, sex differences have emerged across blocks with male participants tending to show faster reaction times for metric decisions and female participants showing faster reaction times for topological decisions (Rybash & Hoyer, 1992). Furthermore, the effect has been found by some to be limited

to the initial block of trials; it has been reported to attenuate for later blocks with the right hemisphere losing its advantage in the metric task due to left hemisphere improvement in that task (Cowin & Hellige, 1994; Kosslyn et al., 1989, Experiment 3; Rybash & Hoyer, 1992). This effect, however, has not been consistently found (Bruyer et al., 1997) or investigated (Hellige & Michimata, 1989; Sergent, 1991). In general, difficulties replicating the task x hemisphere interaction predicted by the two-process theory of high-level visual processing can be attributed to changes in equipment, procedure, participant characteristics and practice suggesting that the effect might be sensitive and transient.

The two- process theory of high-level visual processing has also been criticized for its rationale. It has been suggested that two separate subsystems for managing visual input are unnecessary. Sergent (1991) showed that, in order to process distances between objects, the coordinate system also processes position and therefore spatial relations as well. Computational models confirmed this (Kosslyn et al., 1992, Experiment 2) but also showed that this was not inconsistent with a two-process model. Where network units and weights were segregated into a split model, the topological and metric tasks were completed with fewer errors than when the network units and weights were intermingled (Kosslyn et al., 1992, Experiment 1). These important computational models will be discussed in more detail in the next section.

Further evidence is available that topological and metric subsystems might not be physiologically dissociable. Using PET imaging, both left and right parietal regions appeared to be active during the metric task with relatively more overall activation found in the right hemisphere, but no difference in activation between the parietal

regions was noted when participants performed the topological task although the scans suggested that the left frontal regions were preferentially involved (Kosslyn et al., 1998). However, automaticity of processing and strategy might have been mediating variables.

Spatial frequency of the input available to each hemisphere has also been identified as a possible confound and alternative explanation for findings that support the two-process theory (Ivry & Robertson, 1998). Ivry and Robertson showed that when the dot was very near the bar, the topological task could only be performed when spatial frequencies had been summated and the higher frequencies extracted. By spatial frequency theory, this would render a left hemisphere advantage or a right hemisphere disadvantage. Metric judgments, on the other hand, could be made using low frequency information because the right hemisphere would only need to determine the distance the dot was from the bar or in the case of a dot that was very near to the bar, whether the dot was discernible at all. Therefore, the left hemisphere with its propensity for higher frequency information would be more efficient at the topological task whereas the right hemisphere with its propensity for lower frequency information would be more efficient at the metric task.

The two-process model of high-level visual processing reflects several important theoretical assumptions. First, the model proposes that the two functional subsystems, the topological and metric subsystems, are a finite class of functions necessary for high-level visual processing. Second, the modification Kosslyn has made to Ungerleider and Mishkin's (1982) model is somewhat counterintuitive; if the spatial relationships among features of a stimulus are critical for its identification, why would not this capability have evolved from the "what" system rather than the "where" system. Third, the theory

assumes stable performance across time. However, the often reported practice effect suggests a number of possibilities; the left hemisphere quickly adapts to the metric task perhaps by employing a topological strategy, the left hemisphere is able to perform coordinate judgments on its own (Cowin & Hellige, 1994), or the left hemisphere dominates processing in general (Hellige & Michimata, 1989). These results raise the possibility that the left hemisphere is more flexible in that it can readily find ways to solve the distance problem presented by the metric task.

Doubtless when Kosslyn first introduced his two-process theory of high-level visual processing, he did not anticipate the reactionary whirl of controversy that it would generate. His rationale was elegant and intuitively reasonable, and not inconsistent with the fundamental tenets of cognitive and physiological psychology. The test of his hypothesis proved out with task x hemisphere interactions attributed at least to the right hemisphere evidencing comparatively better performance than the left on metric judgments. Furthermore, his findings have been replicated albeit with certain limitations. However, it was perhaps those limitations and the delicacy of the effect that has drawn the most attention and prompted the most criticism. Fortunately, these very criticisms, taken constructively, have also served as the springboard to a new conceptualization of spatial attention and its association with the characteristics of stimuli.

#### Attentional Bin Theory

Bin theory, as I have called it here, derives from the receptive field hypothesis. The receptive field hypothesis holds that housed within primary sensory cortices are configurations of cells that respond to specific characteristics of a stimulus. Receptive fields vary in size and consequently temporal and spatial resolution but are considered to

be equivalently distributed across the hemispheres. However, the activation of receptive fields of a particular size is likely task dependent with tasks that are most efficiently performed using relatively larger receptive fields being lateralized to the right hemisphere and tasks that are most efficiently performed using relatively smaller receptive fields being lateralized to the left hemisphere. The concept of relativity is important because it necessitates a comparison function that will allow a determination of the task requirements and facilitate the assignment of the task to one hemisphere or the other.

Bin theory posits an attentional mechanism which selects input from receptive fields based on task demands. The selected information is delivered to the hemispheres in “bins” which describe either small discrete or large diffuse regions of space. Whether the task is processed by the left hemisphere or the right depends upon whether the task is best performed using small discrete bins or large diffuse bins because the left hemisphere is posited to be more efficient processing input through small discrete bins and the right hemisphere is posited to be more efficient processing input through large diffuse bins. In other words, if completion of a task is best accomplished using input from large diffuse bins, the right hemisphere will perform the task better than the left, but if the task is best accomplished using input from small discrete bins, the left hemisphere will perform the task better than the right. In terms of spatial judgments, bin theory holds that the topological task is best performed using input from small discrete bins, so the left hemisphere performs this task better. On the other hand, the metric task is best performed using input from large diffuse bins, so the right hemisphere performs this task better (Chabris & Kosslyn, 1998).

The origins of bin theory were truly serendipitous. In addition to finding better performance in split networks, Kosslyn, Chabris et al. (1992) quite unexpectedly and inexplicably, noticed that topological judgments seemed to be more difficult for the network when the elements of the stimulus were within two units of each other. The lack of theoretical explanation for this prompted a third study that examined the effects of coarse coding. Coarse coding is the term used to describe the means by which large overlapping receptive fields create “smooth bands” of possible responses consequently allowing for more precision in responding (Kosslyn, 1990; O’Reilly, Kosslyn, Marsolek & Chabris, 1990). Although these networks did not distinguish discrete from diffuse bins, receptive fields developed by networks trained to the metric task were about twice as large as those developed by networks trained to the topological task. In fact, the receptive fields developed by the metric network had a radius of 9.7 units, and the receptive fields developed by the topological network had a radius of only 4.8 units, a statistically significant difference in size (Kosslyn et al. 1992, Experiment 3). In a follow-up examination, networks with large receptive fields performed the metric task better than networks with small receptive fields, but networks with small receptive fields were only marginally better than those with large receptive fields at performing a topological task. This finding is consistent with the typical effect found in tests of the two-process theory of high-level visual processing (Cowin & Hellige, 1994; Hellige & Michimata, 1989; Kosslyn et. al., 1989; Rybash & Hoyer, 1992) and has been supported by subsequent tests of bin theory as well (Kosslyn, Chabris, Jacobs, Marsolek & Koenig, 1995).

To examine Sergent's (1991) previously found luminance effect, Kosslyn et al. (1992, Experiment 4a) hypothesized that the hemispheres might differ in terms of their modulation transfer functions (MTFs) creating little overlap of functions between the hemispheres under low luminance (low contrast) conditions indicating a functional separation of large right hemisphere and small left hemisphere receptive fields. At higher luminance, on the other hand, when contrast was high, the MTF for each hemisphere would show considerable overlap indicating that both hemispheres, in other words both large and small receptive fields, were able to perform the tasks. On the other hand, it is possible, they speculated, that the loss of asymmetry in spatial judgments under high contrast conditions might be due to the recruitment of more of the same hemisphere specific types of receptive fields. For example, the right hemisphere would recruit more large receptive fields (large large overlap) and the left hemisphere would recruit more small receptive fields (small small overlap) to facilitate task performance under high spatial frequency or high contrast conditions.

To test whether the hemispheres recruited like receptive fields under high luminance conditions, two network models were developed, a mixed model and a homogenous model. For the mixed model, high luminance, operationalized as greater contrast, was assumed to activate both large and small receptive fields thereby eliminating hemispheric differences in spatial judgment. For the homogenous model, greater contrast was assumed to activate more neurons of the same size thus maintaining a hemispheric asymmetry in spatial judgments. If the loss of asymmetry under high luminance conditions was due to the recruitment of small receptive fields in addition to the large by the right hemisphere and large receptive fields in addition to the small by

the left hemisphere, Kosslyn et al. expected to find a loss of asymmetrical performance when both receptive field sizes were activated for each task. If the loss of asymmetry under high luminance conditions was due to recruitment of additional large receptive fields by the right hemisphere and small receptive fields by the left hemisphere, they expected to find a loss of asymmetrical performance of the tasks when either the large large networks or small small networks were running. Their results were consistent with their second hypothesis; that is, under high contrast conditions, asymmetry in spatial judgment was lost for homogenous networks. They interpreted these results as an indication that under conditions of high luminance, asymmetrical performance of spatial judgments was lost because of secondary recruitment of large receptive fields by the right hemisphere and secondary recruitment of small receptive fields by the left hemisphere. They concluded that coarse coding, in effect then, is a process not limited to input from large receptive fields but rather is available for input from small receptive fields as well.<sup>1</sup>

The results of this set of network simulations led to a reformulation of the two-process theory. The theory now includes a more refined role for attention as a mechanism which assesses task demands and differentially facilitates the extraction or

---

<sup>1</sup> The network modeling of two-process theory also poses a number of interpretive challenges. First, by predetermining the weights between input units and hidden layers, definitive information was presented to the hidden input units. Because the networks could have been operating on this definitive information rather than spatial relations among input units, definitive information confounded both the split/unsplit network test and the large/small receptive field test (Cook, Fruh & Landis, 1995). A second challenge relates more to the logic of the methodology. The test of these models could arguably be considered somewhat tautological. Kosslyn et al. (1992) concluded that their computational models showed a dissociation between topological and metric spatial subsystems, but in examining other confounding variables such as receptive field size and luminance, they operationalized performance by the right and left hemispheres as metric and topological tasks respectively which were the conceptual objects of investigation in the first place.

flow of the necessary information into high-level visual processes (Cave & Kosslyn, 1989). It is argued that it does this by adjusting the size of the “input apertures” to either large or small bins which are processed with different degrees of efficiency across the hemispheres.

However, output from this attentional mechanism has been shown to vary with contrast and luminance raising speculation that asymmetry in spatial judgment might be due to spatial frequency. At low luminance, stimuli project fewer high spatial frequencies, so the asymmetry in spatial judgment might be due to proportionally more low frequency input. Similarly, at high luminance, the availability of high spatial frequencies might be responsible for symmetrical high-level visual processes. This explanation changes the function of the attentional mechanism in one important way. Instead of altering the size of the bins to accommodate task relevant receptive field sizes, the attentional mechanism filters the frequency of the incoming information to accommodate task relevant frequency requirements. Whether the attentional mechanism mediates variations in size of the receptive fields or variations in spatial frequencies in order to perform topological and metric judgments is the question being examined here.

## EXPERIMENT 1

Whether spatial frequency can be dissociated from bin size remains an empirical question. That they are related at some physical level is undisputed, but whether the relationship as defined by the mathematics of Fourier analysis is predictable at a functional level is unclear. Evidence is accumulating to suggest that spatial frequency processing and attention to receptive fields are asymmetrically organized, but one of the fundamental difficulties in dissociating the lateralization of attentional bins from the lateralization of spatial frequency is that they must be examined in the context of tasks which are themselves invariably asymmetrically distributed. The purpose of this experiment was to determine if spatial frequency and bin theory could be dissociated by pitting hemispherically consistent task by hemisphere combinations against hemispherically inconsistent combinations of bin and frequency in a series of dissociations within a single design.

One previous attempt to dissociate bin theory from spatial frequency theory using topological and metric spatial judgments is reported. Kosslyn, Anderson, Hilliger and Hamilton, (1994) attempted to distinguish bin theory from both spatial frequency theory and global precedence theory. In this section, the parts of this experiment that pertain to bin and spatial frequency theory will be described in considerable detail, highlighting several major weaknesses in the design and conclusions.

Kosslyn et al. (1994) created stimuli consisting of two consecutively presented lines (1 cm long). The lines were presented at either parallel (same) or perpendicular (different) angles to each other at a near distance of .9 cm or a far apart distance of 5.3 cm. Each line was presented in rapid succession either to the left or the right of, or above

or below central fixation. Kosslyn et al. hypothesized that if bin theory were correct, far apart pairs presented to the right hemisphere would be judged same or different more quickly than far apart pairs presented to the left hemisphere and near pairs presented to the left hemisphere would be judged same or different more quickly than near pairs presented to the right hemisphere. This result, they claimed, would be contrary to expectations of spatial frequency which predicted no difference in the effect of line distance across the hemispheres because the lines were presented at the same spatial frequency in each hemisphere. They found that reaction times for the left hemisphere were longer for the far apart stimulus and shorter for the near stimulus compared to the right hemisphere. Based on these findings, they concluded that the left hemisphere was specialized for processing input through small receptive fields.

These results and the conclusion that Kosslyn et al. (1994) draw from them warrant further comment. First, as Kosslyn et al. state, their hypothesis was based on two important assumptions. The first assumption was that the right hemisphere tends to process the outputs of neurons with larger receptive fields. This is less of an assumption and more an implicit part of the hypothesis, so will not be discussed any further. The second assumption is more critical; they assumed that when two successive stimuli were processed by the same neurons, subjects would respond faster than if the stimuli were processed by different neurons. In other words, if the two lines of the stimulus fell within the same receptive field, they would be processed more quickly than if they fell in different receptive fields. Whether the two lines of the stimulus in either the near or far apart condition activated the same receptive field is not known. Assuming the manipulation was effective, the length of the inter-stimulus interval, if not of sufficient

duration, could also create an interference effect rather than a facilitative effect.

Unfortunately, the duration of the inter-stimulus interval is not reported.

A second criticism of the conclusions drawn in Kosslyn et al. (1994) relates more to the theoretical propositions of bin theory. The manipulation might not have accurately reflected what was originally intended by bin theory. Bin theory posits that the bins are not only spatial in nature but also attentional; the bins represent attention to space rather than simply the activation of receptive fields. Presenting elements of a stimulus sequentially and far from each other does not guarantee that both elements were attended by the same bin. In order to ensure that attention was varied by bin size, a modified directed attention paradigm would have been more appropriate. The modification would simply involve warning the participant to expect a large or small distance between the bars.

Finally, the conclusion that the results are inconsistent with spatial frequency is premature. In fact, the results would be expected if spatial frequency theory holds. Consider that spatial frequency of input decreases as visual angle from fixation increases. This means that in the far condition, the peripheral line is presented to the visual cortex in a more degraded condition than the peripheral line in the near condition. If, as spatial frequency theory espouses, the right hemisphere is specialized for interpreting low frequency input, a right hemisphere advantage would be expected in the far condition because the left hemisphere would be disadvantaged. Given that both bin theory and spatial frequency can adequately describe the results, the dismissal of spatial frequency theory as an explanation for their results is not justifiable.

Given these difficulties, their conclusions with respect to the operation of attentional bins in high level visual processing should be considered tentative at best. Whether input into high level systems is determined by the scope of an attentional bin or by the specific spatial frequencies projected by the stimulus remains an empirical question and fodder for a more rigorous methodology. This methodology must predict opposing results but within the context of asymmetrical spatial judgment, bin sizes and spatial frequencies. Such a methodology will be elucidated next.

### The Double Double Dissociation

The purpose of laterality research is to identify differences in the way the hemispheres perform certain functions. Much of this research examines task relevant functions. For example, verbal tasks are thought to be generally mediated by the left hemisphere while non-verbal tasks are thought to be generally mediated by the right hemisphere. These studies take the basic design of a 2 (right hemisphere, left hemisphere) x 2 (proposed right hemisphere task, proposed left hemisphere task). Another large proportion of laterality research is committed to uncovering hemispheric differences in processing stimulus characteristics. For example, the left hemisphere is thought to process higher spatial frequencies than the right. These studies typically take the basic design of a 2 (right hemisphere, left hemisphere) x 2 (proposed right hemisphere input condition, proposed left hemisphere input condition).

These designs endeavor to answer questions about which hemisphere performs which task better or which hemisphere processes which input condition better. However, they disregard possible task x input condition interactions. Task x hemisphere designs assume that input conditions have no effect on task performance and hemisphere x input

condition designs assume that the task has no effect on the processing of the input conditions. In other words, interactions found for task x hemisphere designs can be attributed to input conditions, and interactions found for hemisphere x input conditions designs can be attributed to task. To address this criticism, task x hemisphere x input condition designs are useful. These designs identify potential interactions between task and input conditions and facilitate a more complete interpretation of task dependent input condition processing by the hemispheres.

The design becomes more complex, however, when the intention is to test opposing hemispheric asymmetries of two input characteristics. The same concerns regarding the confounding effects of asymmetrically distributed task processing apply, so task must be considered as a variable in the analysis. A series of three-way analyses could be conducted, one for each input condition, but a between groups design introduces error which as in the case of topological and metric spatial tasks has been shown to affect the emergence of task x hemisphere effects (Neibauer & Christman, 1998). Furthermore, this does not incorporate a means for examining potential interactions between input characteristics. In order to examine potential interactions, a four-way analysis is needed between task, hemisphere, the first input condition and the second input condition.

Pitting two asymmetrically distributed input characteristics against each other by measuring performance on asymmetrically distributed tasks requires a design that can facilitate the interpretation of task x hemisphere effects and hemisphere x input condition where there are two different input conditions. In the present context, the design must incorporate tests for the effects of task (metric and topological) x

hemisphere (right and left) and hemisphere (right and left) x bin size (large and small) x frequency (high and low). In effect, this pattern of tests predicts a four-way interaction between task, hemisphere, bin size and spatial frequency.

The four-way interaction is a necessary condition but not a sufficient one because within the four-way interaction, particular patterns are predicted. Predictions for the task x hemisphere interaction derive from two-process theory. Two-process theory predicts a left hemisphere advantage for the topological task and a right hemisphere advantage for the metric task. The bin x frequency interaction is governed by a mathematically defined relationship between bin size and spatial frequency; as the size of a stimulus increases, the proportion of low spatial frequencies in the stimulus also increases and as the size of a stimulus decreases, the proportion of high spatial frequencies increases. Essentially, large bin and low spatial frequency vary together as do small bin and high spatial frequency. Both bin theory and spatial frequency theory predict hemispheric asymmetries in the processing of this fundamental relationship. Bin theory predicts better performance by the right hemisphere under large bin conditions and better performance by the left hemisphere under small bin conditions. Spatial frequency theory predicts better performance of the right hemisphere under low spatial frequency conditions and better performance by the left hemisphere under high spatial frequency conditions. If all orthogonal pairs of bin size and spatial frequency conditions are created, both bin theory and spatial frequency theory predict better performance by the right hemisphere under large bin, low frequency conditions and by the left hemisphere under small bin, high frequency conditions. Large bin, low frequency and

small bin, high frequency can then be said to be hemispherically consistent because the level of each factor in each combination predicts the same hemispheric advantage.

If this is the case, the combinations of large bin, high frequency and small bin, low frequency would be hemispherically inconsistent. Specifically, bin theory predicts a double dissociation with a right hemisphere advantage under large bin, high frequency and a left hemisphere advantage under small bin, low frequency conditions. Spatial frequency theory, on the other hand, predicts a double dissociation with a right hemisphere advantage under small bin, low frequency conditions and a left hemisphere advantage under large bin, high frequency conditions. In other words, the direction of the double dissociation predicted by bin theory is opposite to that predicted by spatial frequency theory. In this way, the dissociation predicted by bin theory is pitted against the dissociation predicted by spatial frequency theory. In effect the dissociations of each theory are dissociated and so the dissociation is essentially a double double dissociation.

Because the inconsistent conditions set up asymmetrical predictions for bin theory that lie in direct opposition to the asymmetrical predictions of spatial frequency theory, the double double dissociation can pit bin theory against spatial frequency theory. However, the test is confounded by the inclusion of tasks that are asymmetrically performed. In other words, an inconsistent combination of task and hemisphere and an inconsistent combination of bin and frequency is confounding because asymmetry across the hemispheres cannot be conclusively attributed to the effect of bin or frequency. However, this confound can be controlled by testing only hemispherically consistent combinations of task and hemisphere. In accordance with two process theory, the consistent task and hemisphere combinations are topological task and left

hemisphere, and metric task and right hemisphere combinations. Hemispheric consistency in the task x hemisphere combination controls for the confounding effect of a task x hemisphere interaction while testing the interaction for the inconsistent combination. The double double dissociation, then, is a test of hemisphere (task consistent) x condition (hemispherically inconsistent).

The double double dissociation essentially establishes a priori predictions of hemisphere (task consistent) x condition (hemispherically inconsistent) interaction where the hemispherically inconsistent conditions are constructed in accordance with theoretical predictions. The direction of the interaction will determine whether bin theory or spatial frequency theory predicts the correct pattern of asymmetry in spatial judgments. However, the interpretation of the double double dissociation relies first on the presence of a four-way interaction showing hemisphere effects for task, bin and frequency and on two conceptual assumptions, the assumption of consistency between task and hemisphere and the assumption of hemispheric inconsistency between bin and frequency.

The two conceptual assumptions of the double double dissociation are task by hemisphere consistency and hemispheric inconsistency in the combinations of bin size and spatial frequency. The first conceptual assumption is that of consistency between task and hemisphere where the task that is presumed to be the more specialized processing domain of a given hemisphere is indeed so. In this study, meeting the consistency assumption means that the hemispheres mediated their preferred tasks as expected based on predictions from two-process theory under all four combinations of bin and frequency. In other words, the assumption of consistency holds that the left

hemisphere performs the topological task more efficiently than the right hemisphere and the right hemisphere performs the metric task more efficiently than the left hemisphere under every condition.

The second conceptual assumption of the double double dissociation is that the inconsistent combinations of input characteristics are indeed hemispherically inconsistent and the consistent combinations of input characteristics are indeed hemispherically consistent. If both bin theory and spatial frequency theory are correct in their predictions, a significant hemisphere (task consistent) x condition (hemispherically consistent) interaction will be found with the right hemisphere outperforming the left under large bin, low frequency conditions and the left hemisphere outperforming the right under small bin, high frequency conditions. If this is found, the large bin, low frequency and small bin, high frequency conditions can be considered hemispherically consistent and the large bin, high frequency and small bin, low frequency conditions are arguably hemispherically inconsistent. If the hemispheric dissociation is not found between large bin, low frequency and small bin, high frequency conditions, then either one of the input characteristics is not asymmetrically distributed or one is distributed in the direction opposite that predicted by theory. In this case, the combinations of large bin, high frequency and small bin, low frequency cannot confidently be said to be hemispherically inconsistent. If a dissociation is found in the opposite direction, then the asymmetrical predictions of at least one of the theories is wrong.

The double double dissociation then predicts a four-way interaction and assumes task x hemisphere consistency and hemispheric inconsistency between bin size and spatial frequency. The assumption of task x hemisphere consistency predicts a task x

hemisphere interaction showing that the right hemisphere is better than the left when performing metric judgments and the left hemisphere is better than the right when performing topological judgments in all four combinations of bin size and spatial frequency. The assumption of hemispheric inconsistency between bin size and spatial frequency predicts a hemisphere (task consistent) x condition (hemispherically consistent) interaction showing better performance by the right hemisphere (metric task) than the left (topological task) under large bin, low frequency and better performance of the left hemisphere (topological task) than the right (metric task) under small bin, high frequency conditions.

### *Hypotheses*

The double double dissociation method facilitates the opposition of two competing a priori hypotheses in a hemisphere (task consistent) x condition (hemispherically inconsistent) ANOVA. First, if bin theory is correct, the right hemisphere (metric task) will perform better under large bin, high frequency conditions and the left hemisphere (topological task) will perform better under small bin, low frequency conditions (Figure 1). If, on the other hand, spatial frequency theory is correct, the right hemisphere (metric task) will perform better under small bin, low frequency conditions and the left hemisphere (topological task) will perform better under large bin, high frequency conditions (Figure 2).

The hemisphere (consistent) x condition (hemispherically inconsistent) test of the double double dissociation provides strong evidence to support one theory's asymmetrical predictions over another. However, it can only be interpreted within the context of a four-way analysis and if the assumptions of consistency between task and

hemisphere and inconsistency between bin and frequency have been established. To this end, if a double double dissociation is found, a four-way interaction will be tested. Following this, the assumption of consistency will be tested in task x hemisphere ANOVAs for each condition. If this assumption is met, the metric task will be performed better by the right hemisphere than the left and the topological task will be performed better by the left hemisphere than the right under each orthogonal combination of bin and frequency (Figure 3). Finally, the assumption of inconsistency will be examined in a hemisphere (task consistent) condition (hemispherically consistent) ANOVA. If this assumption is met, the right hemisphere (metric task) will perform better than the left (topological task) under large bin, low frequency conditions and the left hemisphere (topological task) will perform better than the right (metric task) under small bin, high frequency conditions (Figure 4).

## Method

### *Ethics*

Approval for this research was obtained by the University Advisory Committee on Ethics in Behavioral Science Research. All participants gave informed consent [Appendix A].

### *Participants*

A total of 70 right-handed participants were tested. Participants were all first year psychology undergraduate students who received course credit for participating. Five participants were eliminated from the analysis; two participants reported that they did not understand the task and asked to be excused, two reported visual problems and one reported a head injury that affected his vision. Of the remaining 65 participants, 28

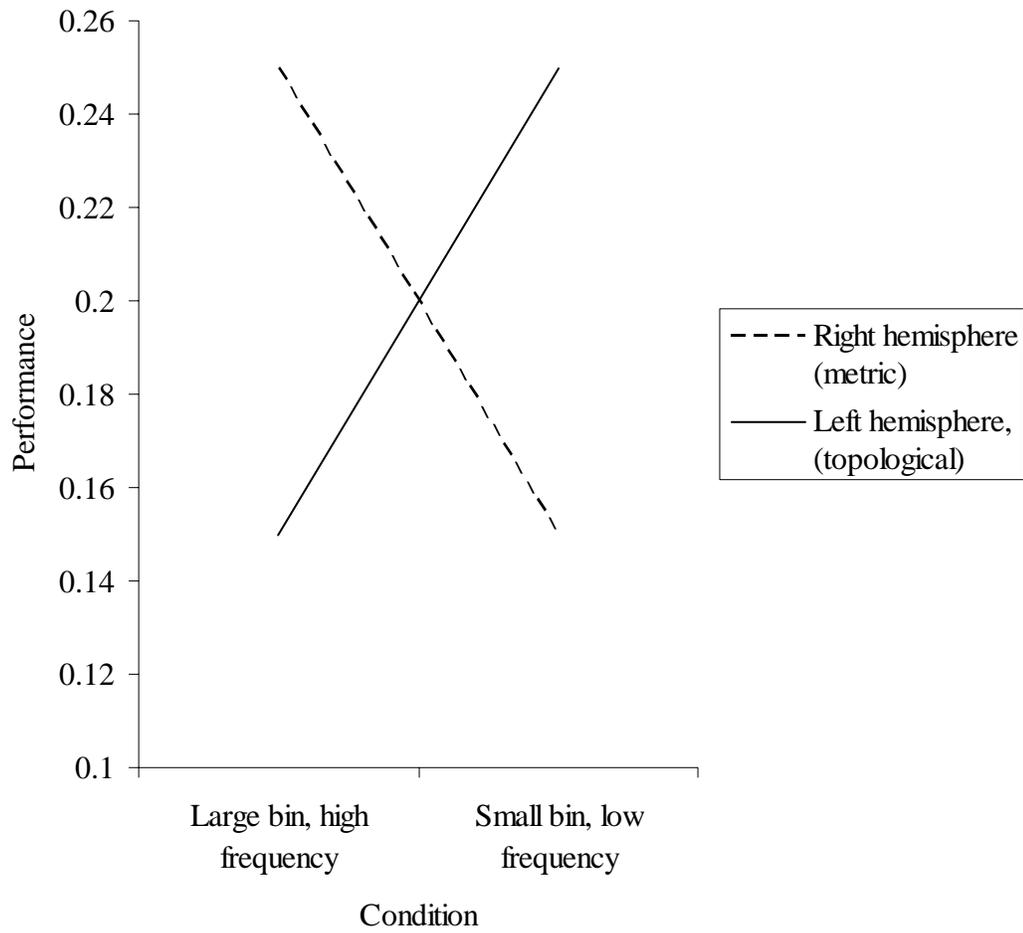


Figure 1. Hypothesized predictions based on bin theory showing better performance under large bin conditions by the right hemisphere (metric task) than the left (topological task) and better performance under small bin conditions by the left hemisphere (topological task) than the right hemisphere (metric task).

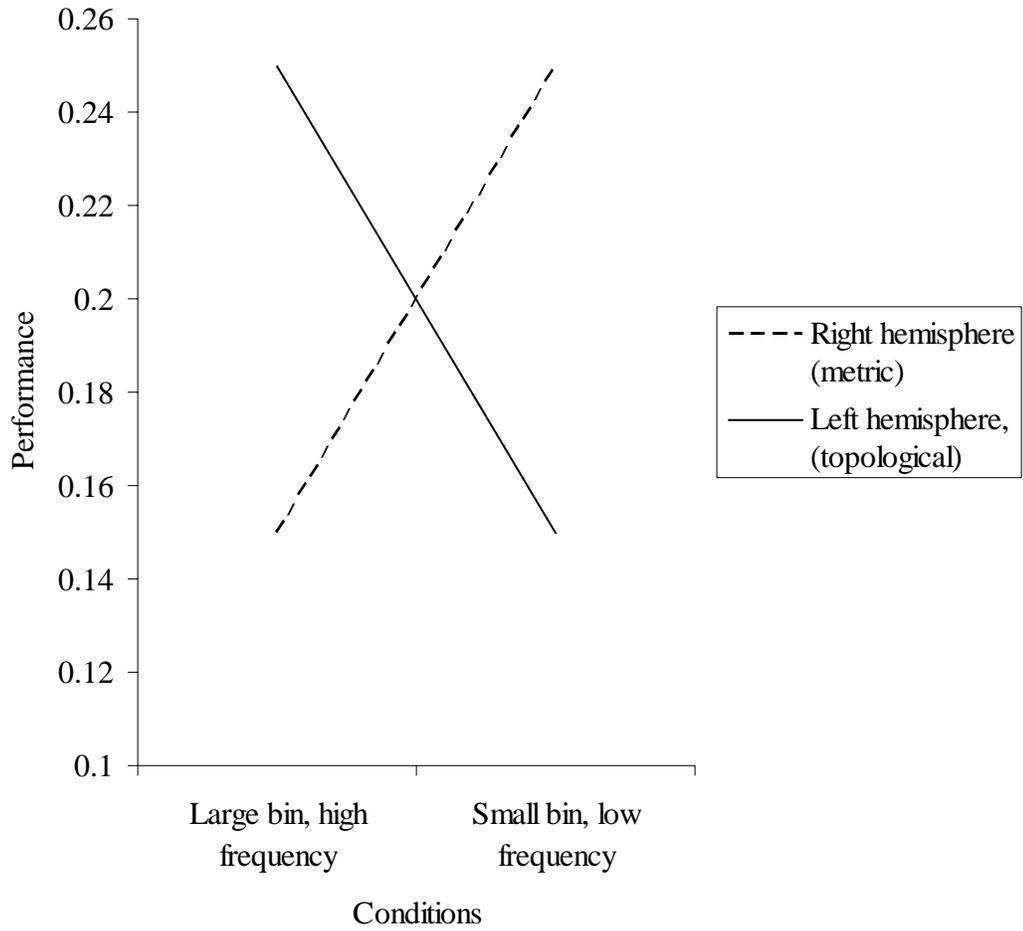


Figure 2. Hypothesized predictions based on spatial frequency theory showing better performance under low spatial frequency conditions by the right hemisphere (metric task) than the left (topological task) and better performance under high spatial frequency by the left hemisphere (topological task) than the right hemisphere (metric task).

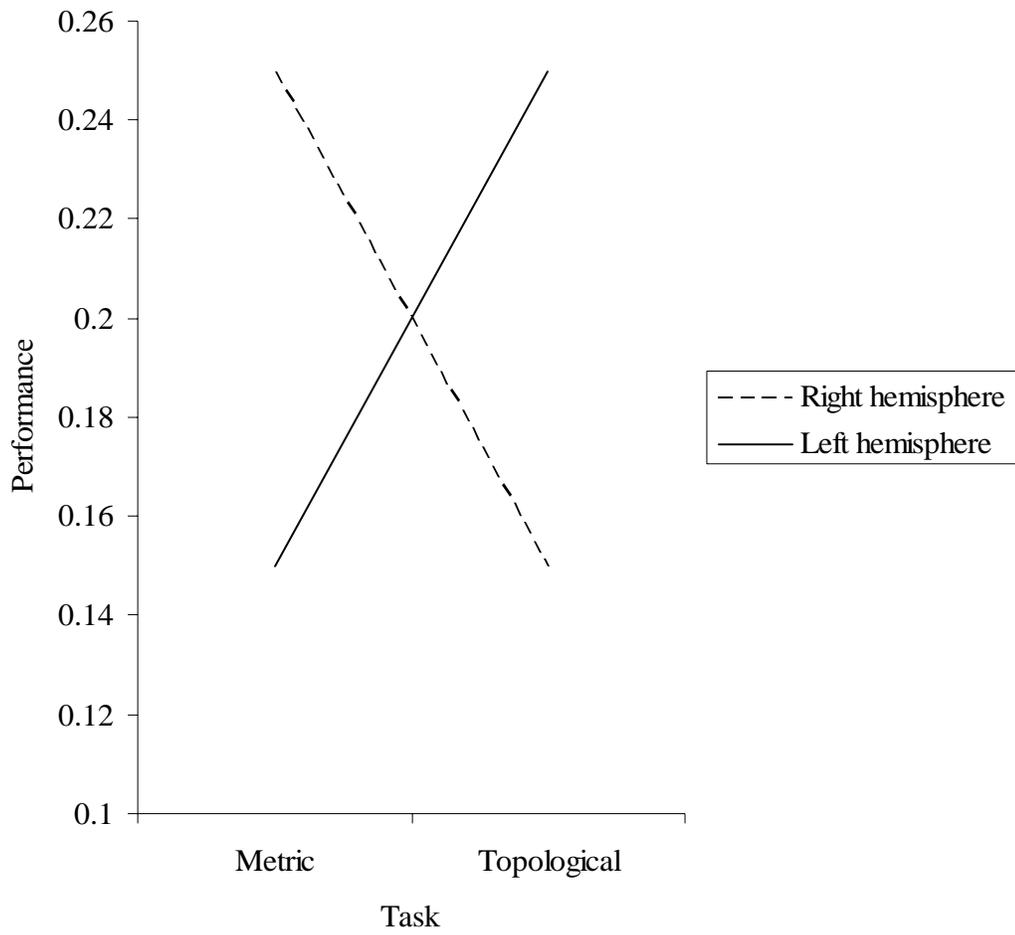


Figure 3. Hypothesized predictions for task x hemisphere consistency for each condition showing better performance of the metric task by the right hemisphere and better performance of the topological task by the left hemisphere.

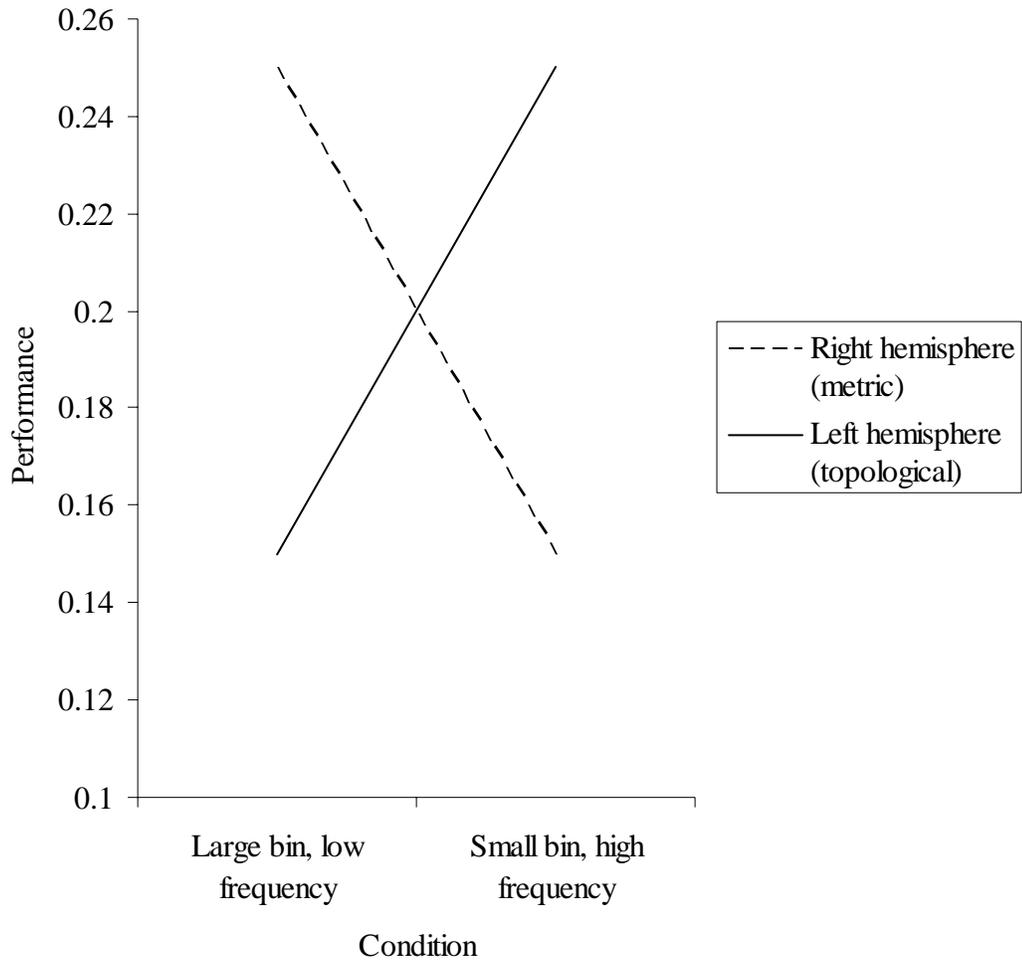


Figure 4. Hypothesized predictions for hemisphere (task consistent) x condition (hemispherically consistent) consistency showing better performance of the right hemisphere (metric task) under large bin, low frequency conditions and better performance of the left hemisphere (topological task) under small bin, high frequency conditions.

were male and 37 were female. Ages ranged from 18 to 45 with a mean age of 19.89 ( $SD = 4.01$ ). The average age of the male participants was 20.32 years of age ( $SD = 5.48$ ). The average age of the female participants was 19.57 years of age ( $SD = 2.40$ ). Analysis of variance (ANOVA) with sex as the fixed factor was non-significant indicating no significant difference in age between male participants and female participants. All participants had normal or corrected to normal vision.

Handedness was examined using a 15 item questionnaire [see Appendix B]. On this questionnaire participants with scores from -30 to -15 were considered strongly left-handed, participants with scores from -15 to 0 were considered weakly left-handed, participants with scores from 0-15 were considered weakly right-handed and participants with scores from 15 to 30 were considered strongly right-handed. Based on this breakdown, 60 participants were considered strongly right-handed and 4 participants were considered weakly right-handed. One participant failed to respond to one question so a total score could not be calculated. However, based on the responses she provided, her total score would fall between 17 and 21 indicating strong right-handedness.

### *Stimuli*

#### *Stimuli Development.*

Pilot testing was undertaken to develop stimuli that would accommodate manipulation in terms of attentional bin size and spatial frequency and also render the predicted task x hemisphere interaction. All piloted stimuli were presented on a 19 inch colour monitor (1024 x 768 pixels) in a quiet darkened testing room. Stimuli were created using Jasc Paintshop Pro and presented as bitmap images using E-Prime Studio

software. The stimuli were white on black and presented 3.75 visual angle from a central fixation plus sign at 150 ms exposure duration.

The purpose of the first pilot study was to determine if the task x hemisphere interaction predicted by two-process theory could be replicated. The stimulus was similar to that used by Sergent (1991). It consisted of a large white round circle with a small dot located in one of 8 possible dot positions arranged along two perpendicular diagonal arrays within the circle. Participants were cued on each trial to judge the location of the dot from one of two randomly selected reference points. In the small bin condition, participants were asked to judge the position of the dot in relation to the centre of the circle. In the large bin condition, participants were asked to judge the position of the dot in relation to the periphery of the circle. For the topological task, participants were asked to judge whether the dot was to the left or right of centre or the periphery and for the metric task, more or less than 4 mm from centre or the periphery. Ten right-handed participants were tested. For reaction time data, no significant effects emerged at all. Similarly for accuracy data, task x hemisphere interactions did not emerge for judgments made from either the central reference point or the peripheral reference point. A main effect emerged for task for centrally referenced judgments,  $F(1, 9) = 4.975, p = .053$ , showing more accurate performance of the topological task ( $M = 0.911, SE = 0.022$  for the topological task and  $M = 0.863, SE = 0.025$ , for the metric task) as well as a main effect for task for peripherally referenced judgments,  $F(1, 9) = 120.496, p < .001$ , showing more accurate performance of the metric task ( $M = 0.831, SE = 0.028$  for the metric task and  $M = 0.536, SE = 0.012$  for the topological

task). The reason for this was near chance responding for the topological task with peripherally referenced judgments (Appendix C).

The second pilot study was undertaken to determine if the task x hemisphere interaction found by Kosslyn et al. (1989) could be replicated using the identical stimuli under the environmental conditions and presentation dimensions in our lab. The stimulus that was used was identical in its dimensions to that used by Kosslyn et al. (1989c; Appendix D) and will be described in more detail later in this section. Sixteen right-handed participants were tested. The topological task required participants to press one button if they judged the dot to be above the line and another if they judged it to be below. The metric task required participants to press one button if they judged the dot to be near the line and another if they judged it to be far from the line. Although no interaction emerged for accuracy data, a task x hemisphere interaction emerged,  $F(1, 13) = 7.136, p = .019$ , for reaction time similar to that found by others (Cowin & Hellige, 1994; Hellige & Michimata, 1989; Kosslyn et al., 1989; Rybash & Hoyer, 1992). This interaction showed faster reaction times for the metric task by the right hemisphere ( $M = 589.254, SE = 29.407$ ) compared to the left ( $M = 617.546, SE = 37.736$ ) and marginally faster reaction times for the topological task by the left hemisphere ( $M = 425.890, SE = 24.606$ ) compared to the right ( $M = 427.828, SE = 24.889$ ).

Finally, an effort was made to determine if the stimuli that were identical to Kosslyn et al.'s (1989) stimuli (in other words, those used in the second pilot study) could be rotated without losing the task x hemisphere interaction. Rotating the stimulus was considered beneficial to the bin manipulation as a means of enhancing attention to a larger area of space. In this pilot test, the same bar and dot stimuli that were used in the

second pilot test were rotated 45 degrees to the left and right. The topological task required participants to press a button if they judged the dot to be to the left of the diagonal line and another if they judged the dot to be to the right of the diagonal line. The metric task required participants to press a button if they judged the dot to be near the line and another if they judged it to be far. Eleven right-handed participants were tested. Looking first at reaction time, a between-subjects analysis testing the effect of rotation showed no task x hemisphere interaction but significant main effects for task,  $F(1, 22) = 20.160, p < .001$ , and hemisphere  $F(1, 22) = 12.550, p = .002$ . Participants responded more slowly in the topological task when the stimulus was rotated ( $M = 558.141, SE = 28.624$  for the rotated and  $M = 426.859, SE = 24.192$  in the vertical orientation) but no effective difference in reaction time was noticed for the metric task. As well, a larger decrement in speed was noted for the right hemisphere in the rotated condition ( $M = 508.541, SE = 24.137$  in the vertical orientation compared to  $M = 587.831, SE = 28.559$  in the rotated orientation). Looking at accuracy data, no significant effect of orientation of the stimulus emerged. When the data for the rotated conditions were examined separately, no task x hemisphere interaction emerged for the accuracy data or the reaction time data (Appendix E). Although no group differences were noted in the task x hemisphere interaction, the loss of the interaction when the stimulus was rotated suggested that had power been sufficient a group difference might have emerged.

The results of pilot testing indicated that minor variations in the stimuli could significantly impact the task x hemisphere interaction predicted by two-process theory. For that reason, the stimuli used in the present study were only minimally altered in

order to accommodate the bin manipulation. The significant task x hemisphere interaction noted in the second pilot study indicated that the environmental conditions under which we tested were solicitous for the emergence of asymmetry in spatial judgments.

*Present Stimuli.*

The stimuli in the present study had to be interpretable in terms of spatial frequency theory, bin theory and Kosslyn's theory of high-level visual processes. To manipulate high-level visual processes, the stimulus included both a metric and topological task. To manipulate attentional bins, the direction of attention had to be moved toward the periphery of the stimulus as well as toward its centre. To manipulate spatial frequency, the stimulus had to be amenable to degradation.

The stimuli were white and were presented on a black background. Luminance was calculated using a Tektronix Narrow Angle Luminance Probe which measures the luminance of a defined field. Combined luminance of the stimulus and background was approximately 4 c/m<sup>2</sup>.

The stimuli for the small bin condition consisted of a white line drawing of a bar 7 pixels long and 3 pixels wide with a small white square measuring 2 pixels x 2 pixels placed in one of 12 designated positions. Six positions fell above the line and six positions fell below. The space between the positions was 1 pixel wide except for the space between the third and fourth squares which was 4 pixels wide. The stimuli for the large bin condition consisted of a white circle measuring 51 pixels in diameter with a small white square measuring 2 pixels x 2 pixels in one of twelve designated positions. Six positions were located above the circle and 6 positions were located below. Like the

bar stimulus, the spaces between the squares was 1 pixel wide except for the space between the third and fourth squares which measured 4 pixels across. The line that formed the circle was 3 pixels wide. Twelve separate picture files for the 12 possible dot locations in the bar and dot stimulus were created using JASC Paintshop Program. As well, using the same program, 12 separate picture files were created for the 12 possible dot locations in the circle and dot stimulus. Frequency was manipulated by blurring the stimulus. [See Appendix F to view all files]

Two separate blocks of trials were run, each block consisting of a set of trials for the topological task and a set of trials for the metric task. Each set consisted of two presentations of either the topological or the metric conditions in each of the 12 possible dot positions. Table 1 lists all orthogonal combinations that were created using each level of each condition: hemisphere of presentation (right and left), bin cue (large and small), and frequency (high and low) producing 16 possible conditions. With 8 conditions per task presented twice in each of twelve dot locations, a stimulus set consisted of 192 trials. Sixteen practice trials with feedback were included at the start of each set. All trials were presented in a random sequence. Tasks were counterbalanced across participants with half of the participants beginning with the topological task and the other half beginning with the metric task.

### *Procedure*

Participants were tested individually in a quiet darkened testing room. The stimuli were presented 3.75 degrees of visual angle from central fixation on an IBM compatible PIII computer with a 19 inch monitor set with a resolution of 1024 x 768

pixels. After signing the consent form, each participant was asked to fill in a handedness questionnaire (Appendix B). Each person was then asked to sit in a comfortable chair

Table 1

*All Conditions Organized by Task, Hemisphere, Bin Size and Frequency*

Condition	Task	Hemisphere	Bin Size	Spatial Frequency
1.	topological	right	large	high
2.	topological	right	large	low
3.	topological	right	small	high
4.	topological	right	small	low
5.	topological	left	large	high
6.	topological	left	large	low
7.	topological	left	small	high
8.	topological	left	small	low
9.	metric	right	large	high
10.	metric	right	large	low
11.	metric	right	small	high
12.	metric	right	small	low
13.	metric	left	large	high
14.	metric	left	large	low
15.	metric	left	small	high
16.	metric	left	small	low

---

and place his or her chin on a chinrest that was positioned 57 cm from the screen and high enough so that the horizontal and vertical midlines of the eyes were aligned with the horizontal and vertical midlines of the computer screen.

At the start of the experiment, the participant was presented with a set of instructions that explained the task. The general instructions oriented the participant to the trial sequence outlining the presentation of a fixation point, a cue and a stimulus. Next, the participant was presented with instructions for the first task. Instructions for the topological task stated that the participants would be asked to judge whether a dot was placed above or below a line or a circle and that they would respond by stating their answer clearly into a microphone. For the metric task, participants were asked to judge whether a dot was more or less than 3 mm from the line or circle again stating their response clearly into a microphone. Participants were instructed to keep their eyes on fixation at all times and to respond as quickly as possible without sacrificing accuracy.

After the instructions were given for the task, participants completed 16 practice trials. Each stimulus presentation followed the same sequence of events. Figure 5 shows the order of presentation for the bar stimulus and Figure 6 shows the order of presentation for the circle stimulus. First, the fixation mark, represented by an exclamation mark located at dead centre of the computer screen, was presented for 400 ms followed by a blank screen for 500 ms. Next, an attentional cue was presented for 600 ms indicating whether the judgment would be in relation to a bar or a circle. If the judgment was to be in relation to a bar, a bar of exactly the same dimensions as the stimulus appeared. If the judgment was to be in relation to a circle, a circle of exactly the same dimensions as the stimulus appeared. Then the stimulus was presented for 150 ms

in either the left or right visual field with the centre of the stimulus at 37.5 mm from the centre of the fixation mark (3.75 degrees visual angle retinal eccentricity) to ensure that foveal orientation did not occur.

Participants responded verbally into a microphone. Their verbal response stopped the computer's internal clock. The time between presentation and response was recorded. Accuracy was recorded by the experimenter who pressed one of two keys in order to record whether the participant responded with "above" or "below" in the topological task, or "more" or "less" in the metric task. After each response, a blank black screen was presented for 2000 ms before the start of the next trial.

#### *Statistical Analysis*

Because of the transient nature of the effect and previously reported gender differences, the data were examined first for effects of block and gender. Then the a priori hypotheses were tested in a 2 x 2 hemisphere (task consistent) x condition (hemispherically inconsistent) repeated measures ANOVA. Next, the data were examined for a four-way (task x hemisphere x bin x frequency) interaction, task x hemisphere interaction in each of the four conditions and a hemisphere (task consistent) x condition (hemispherically consistent) interaction.

#### *Results*

All data were analyzed on a Pentium III IBM compatible PC using E-Prime, Microsoft Excel 2003 and Statistical Package for Social Science 13.0 software. On some trials, participants coughed, cleared their throat, vocalized or otherwise tripped the timer in the computer before giving their response. These responses were identified by the tester and eliminated. To ensure that mean scores for each participant were reliable, each

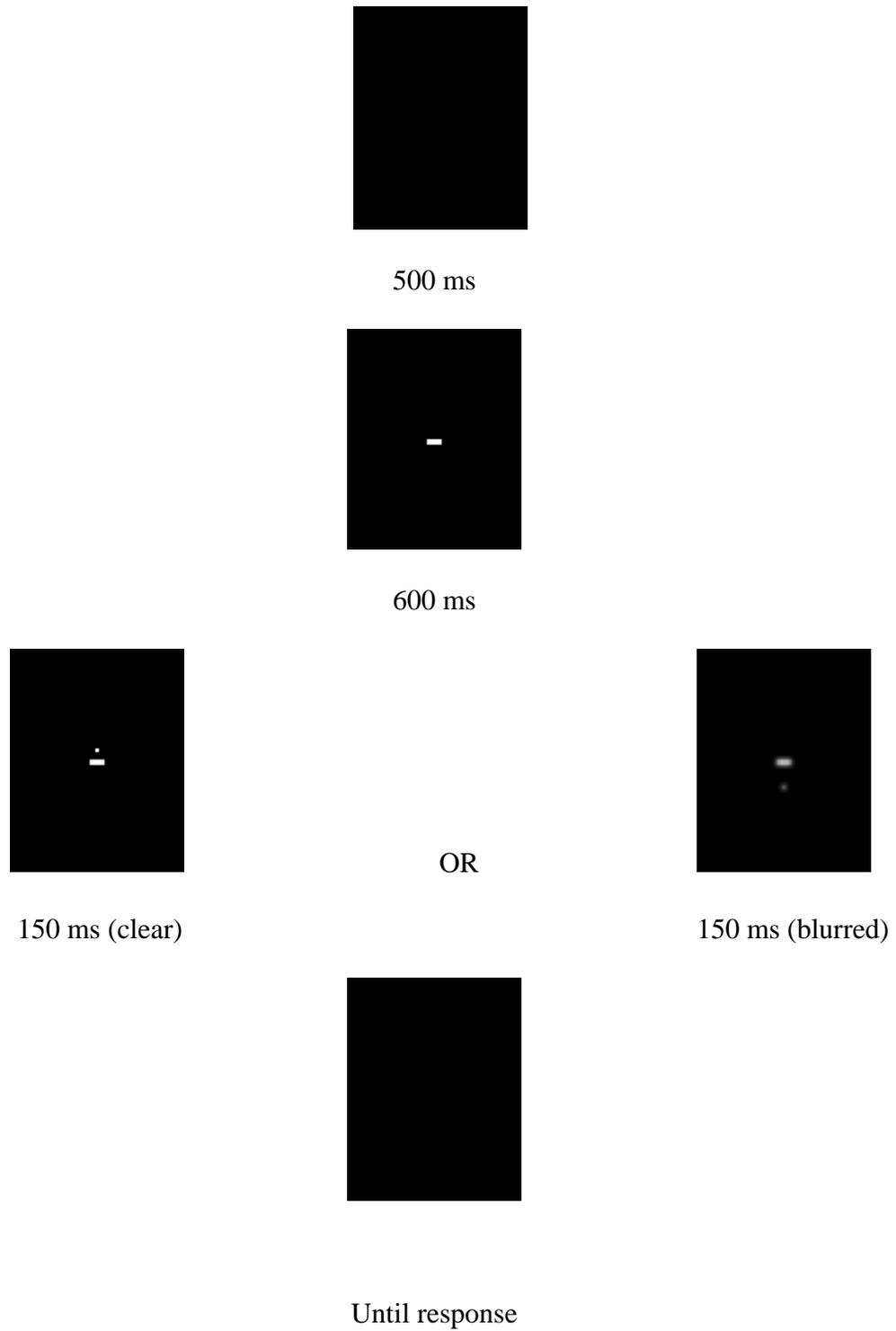


Figure 5. Sequence of presentation showing fixation, cue and stimulus for the bar and dot stimulus. ms = milliseconds.

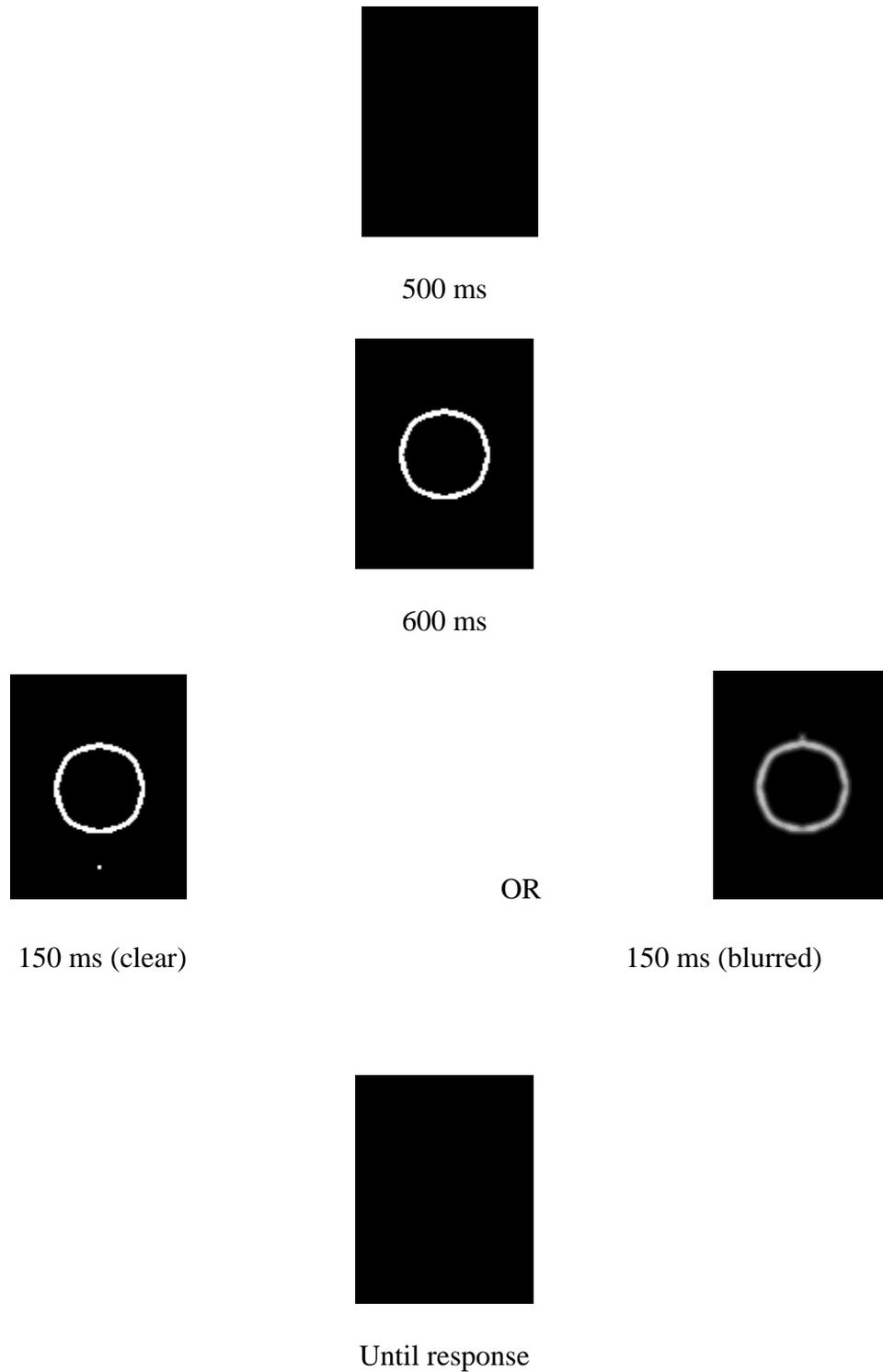


Figure 6. Sequence of presentation showing fixation, cue and stimulus for the circle and dot stimulus. ms = milliseconds

participant's data set was checked for outliers. Means and standard deviations for each task in each block were calculated and any data points that fell beyond 2 *SD* from the mean for each task for each block were deemed to be outliers. From a total of 60,734 data points, 2,496 points were deleted. All data were then averaged for each participant for each condition defined by task, block, visual field, bin size and frequency.

All data were examined for normality. Significant deviations (Shapiro-Wilks) from normality were found on 9 metric conditions and all topological conditions. The general trend was toward negative skew and leptokurtosis in all cases. Given this, the data were again checked for outliers. Outliers were again defined as more or less than 2 *SD* but from the mean of each variable. Using this criteria, 4 data points were eliminated for subject 1, 1 for subject 3, 9 for subject 4, 25 for subject 17, 7 for subject 20, 6 for subject 23, 18 for subject 34, 3 for subject 48, 9 for subject 68, 27 from subject 70, and 17 from subject 71 for a total of 126 excluded data points leaving 2114 data points remaining. After eliminating outlying values, significant deviations from normality were found on only 1 metric condition and 4 topological conditions out of a total of 32 conditions. The remaining 27 conditions had distributions that approximated normal.

### *Preliminary Analyses*

Before proceeding to an analysis of the a priori hypotheses, the data were examined for the purposes of comparison with previous research for reaction times and accuracy.

#### *Reaction Times.*

Mean reaction times for all variables are listed in Appendix G. Looking specifically at the small bin, high frequency conditions in the present study which were

comparable to the conditions under which Kosslyn et al. (1989) presented their stimuli, reaction times were generally comparable showing the same pattern of faster reaction times for the topological task than for the metric task (see Table 2). However, reaction times were notably shorter for the second block of the present study compared to the first whereas, no particular pattern of improvement emerged from the first to the second block of Kosslyn et al. In addition, in the present study, the right hemisphere was considerably slower in mean response time for block 1 compared to block 1 of Kosslyn et al.'s (1989) study but appeared to speed up to a comparable rate by the second block.

#### *Accuracy.*

Appendix G shows that, in the present study, accuracy scores tended to be high across all conditions. Kosslyn et al. (1989) did not examine their data for accuracy. However, looking at the conditions in the present study that simulated Kosslyn et al.'s (1989) conditions, accuracy was generally high with higher accuracy in the second block of trials and consistently higher accuracy when performing topological judgments (see Table 3). Accuracy was marginally better when the metric task was performed by the right hemisphere across both blocks and when the topological task was performed by the left hemisphere in the second block.

#### *Reaction time and Accuracy Correlations.*

Two significant positive Pearson product-moment correlations were found between variables within the data set suggesting a speed/accuracy trade-off in the performance of the metric task for the second block [see Tables 4 and 5]. Efficiency scores were created by dividing reaction time into accuracy and multiplying by 100 for all reaction time and accuracy variable pairs.<sup>2</sup> This operation rendered a dividend

Table 2

*Mean Reaction Times from Kosslyn et al. (1989) Compared to Comparable Conditions (Small Bin, High Frequency) in the Present Study.*

Task x Hemisphere	Kosslyn et al. (1989)*		Present study	
	Block 1	Block 2	Block 1	Block 2
	(24 trials)	(24 trials)	(48 trials)	(48 trials)
	<i>M</i>	<i>M</i>	<i>M</i>	<i>M</i>
Metric				
x left hemisphere	580	540	589	539
x right hemisphere	530	540	590	537
Topological				
x left hemisphere	430	430	442	414
x right hemisphere	440	430	449	418

\*derived from Figures 4 and 6 (Kosslyn et al. 1989)

Table 3

*Mean Accuracy Scores (Standard Deviations) for Task x Hemisphere for the Comparable Conditions to Kosslyn et al. (1989)*

Task x Hemisphere	Block 1	Block 2
Metric		
x left hemisphere	.85(0.09)	.86(0.08)
x right hemisphere	.87(0.09)	.88(0.08)
Topological		
x left hemisphere	.98(0.04)	.99(0.03)
x right hemisphere	.98(0.03)	.98(0.03)

Table 4

*Correlation Coefficients for Reaction Time and Accuracy for the Topological**Conditions (n = 70)*

Condition			Block 1	Block 2
Hemisphere	Bin size	Frequency		
1. Right	large	high	-.054	-.152
2.		low	.165	-.226
3.	small	high	-.041	-.057
4.		low	-.190	-.057
5. Left	large	high	-.026	-.019
6.		low	.185	-.149
7.	small	high	-.019	-.054
8.		low	-.056	-.089

\*No significant correlations at  $p < .05$

Table 5

*Correlation Coefficients for Reaction Time and Accuracy for the Metric Conditions (n = 65)*

Condition			Block 1	Block 2
Hemisphere	Bin size	Frequency		
1. Right	large	high	.200	.232
2.		low	.029	.227
3.	small	high	.020	.109
4.		low	-.095	.122
5. Left	large	high	.058	.218
6.		low	.029	.249* (p = .046)
7.	small	high	.027	.282* (p = .023)
8.		low	.018	.217

\*p < .05

interpreted such that high scores represent better efficiency and lower scores represent poorer efficiency. All subsequent analyses were performed on efficiency scores.

#### *Normality.*

Efficiency scores for each variable were examined for normality in their distributions using Shapiro-Wilks statistics. Significant t statistics were noted for several variables indicating distributions that did not approximate normal [Appendix H]. Among these non-normal distributions were several variables that were critical to the interpretation of the double double dissociation and its assumptions. Although ANOVA is relatively robust to violations of normality, the planned comparisons are not. For that reason all scores were transformed using  $\log^{10}$ . All subsequent analyses were conducted using  $\log^{10}$  transformed efficiency scores. This resulted in efficiency being represented in negative values with the larger values representing higher efficiency.

#### *Block effect*

In examining for differences between Block 1 and Block 2, a significant main effect for block was found,  $F(1, 54) = 726.852, p < .001$ , showing better efficiency on block 2 trials ( $M = -0.647, SE = 0.008$ ) than block 1 ( $M = -0.816, SE = 0.008$ ). Paired t-tests with corrected alpha set at .002 (Bonferroni) showed that all pairs differed significantly with improved efficiency consistently noted for Block 2 (Appendix I). These results are consistent with a practice effect but because of the reported transience of the task x hemisphere effect, both blocks were analyzed but analyzed separately.

---

<sup>2</sup> The decision to use efficiency scores was not without contention. Given that 1.6 significant correlations can be expected by chance alone, some suggested that conversion to efficiency scores was an unnecessary manipulation of the data. However, efficiency scores are arguably a more accurate reflection of the dualistic nature of processing and ultimately facilitated a comparison with the within-subjects data from Experiment 3 where clear evidence of co-linearity was found showing decreased accuracy with faster responding under some conditions and decreased accuracy with slower responding under others.

#### *Block 1.*

Block 1 was analyzed first for sex differences. Equality of covariance matrices (Box's *M*) and sphericity (Mauchley's) were assumed. No significant main effect of sex was found but a significant sex x hemisphere x bin x frequency interaction was found,  $F(1, 54) = 7.148, p = .010$ . Under high spatial frequency conditions, both male participants and female participants tended to perform better when large stimuli were presented to the left hemisphere than the right and when small stimuli were presented to the right hemisphere. Under low spatial frequency conditions, the pattern was the same for male participants in that they performed better with the left hemisphere when bin size was large and better with the right hemisphere when bin size was small. Female participants, on the other hand, performed better with the left hemisphere when bin size was small and with the right hemisphere when bin size was large [Appendix J]. Because of this interaction, male and female participant data were examined separately.

#### Male Participants

The test of the a priori hypotheses revealed a hemisphere (task consistent) x condition (hemispherically inconsistent) interaction,  $F(1, 23) = 19.842, p < .001$ , as shown in Figure 7. This interaction showed relatively better efficiency for the left hemisphere (topological task) under large bin, high frequency conditions ( $M = -0.650, SE = 0.014$ ) than small bin, low frequency conditions ( $M = -0.725, SE = 0.016$ ) when compared to the right hemisphere (metric task) under large bin, high frequency ( $M = -0.834, SE = 0.017$ ) and under small bin, low frequency ( $M = -0.858, SE = 0.017$ ). Differences across conditions were significant for both the left hemisphere,  $t(23) = 10.386, p < .001$ , and the right hemisphere,  $t(25) = 2.491, p = .020$ .

No significant four-way interaction emerged, nor any hemisphere effects. A task x

frequency interaction emerged,  $F(1, 22) = 4.182, p = .053$ , showing relatively better performance of the topological task under high frequency conditions than low frequency conditions compared to the metric task under high frequency conditions) and low frequency conditions. A task x bin interaction was also found,  $F(1, 22) = 17.783, p < .001$ , showing relatively better performance of the topological task under large bin conditions than small bin conditions compared to the metric task under large bin conditions and small bin conditions. Consistent with these interactions, main effects were found for task,  $F(1, 22) = 181.672, p < .001$ , with better performance of the topological task than the metric task, for bin,  $F(1, 22) = 23.252, p < .001$ , with better performance under large bin conditions than small, and for frequency,  $F(1, 22) = 94.800, p < .001$ , with better performance under high frequency conditions than low frequency. No significant tasks x hemisphere interactions were noted under any conditions nor was a hemisphere (task consistent) x condition (hemispherically consistent) interaction found [Appendix K].

#### Female participants

The test of the a priori hypotheses showed a significant interaction,  $F(1, 32) = 6.696, p = .014$ , (Figure 8). Similar to that found for male participants, the interaction demonstrated relatively better performance of the left hemisphere (topological task) under large bin, high frequency conditions ( $M = -0.624, SE = 0.011$ ) than small bin, low frequency conditions ( $M = -0.678, SE = 0.010$ ) compared to the right hemisphere (metric task) under large bin, high frequency conditions ( $M = -0.836, SE = 0.012$ ) and small bin, low frequency conditions ( $M = -0.859, SE = 0.015$ ). Paired t-tests showed significant

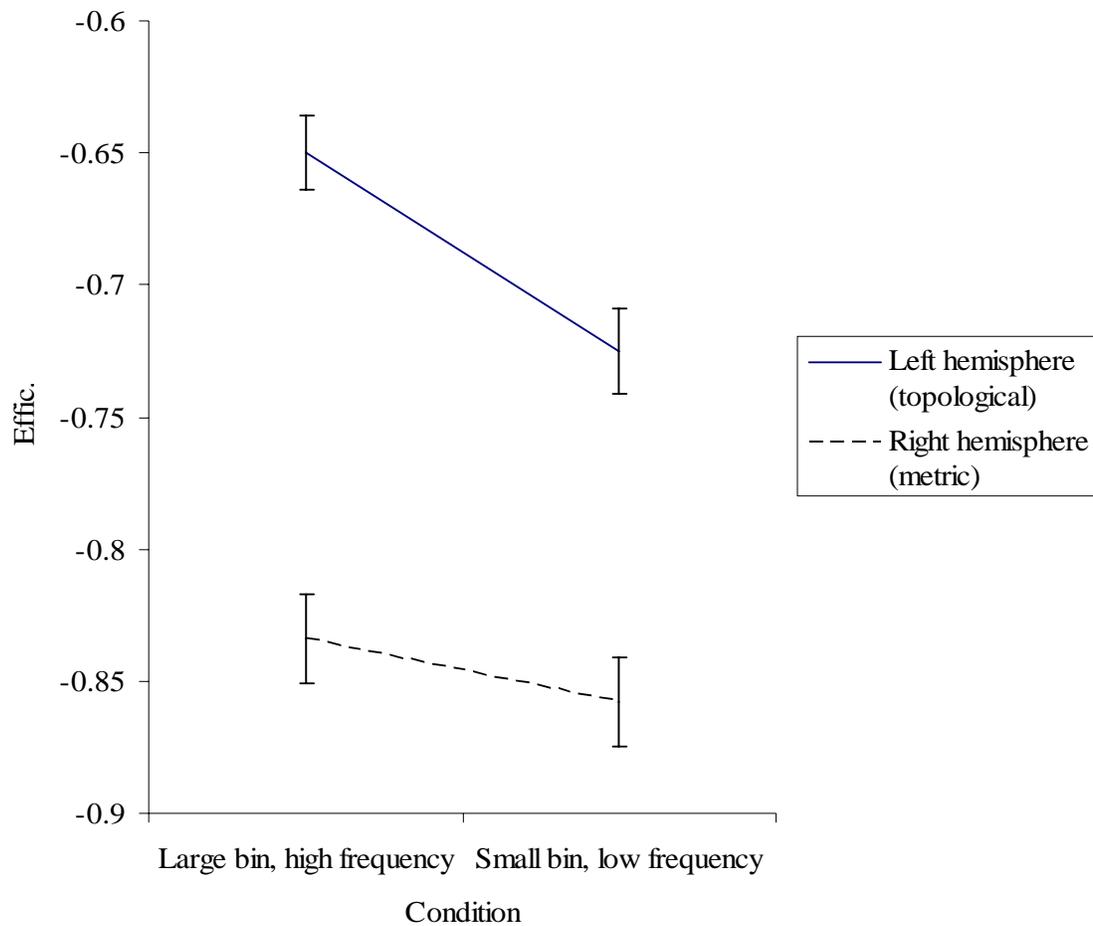


Figure 7. Log transform efficiency means for male participants in block 1 showing an interaction between hemisphere (task consistent) and condition (hemispherically inconsistent). Performance was better for the left hemisphere (topological task) and under large bin, high frequency conditions but proportionally better for the left hemisphere (topological task) under large bin, high frequency conditions. Effic. = Transformed efficiency scores.

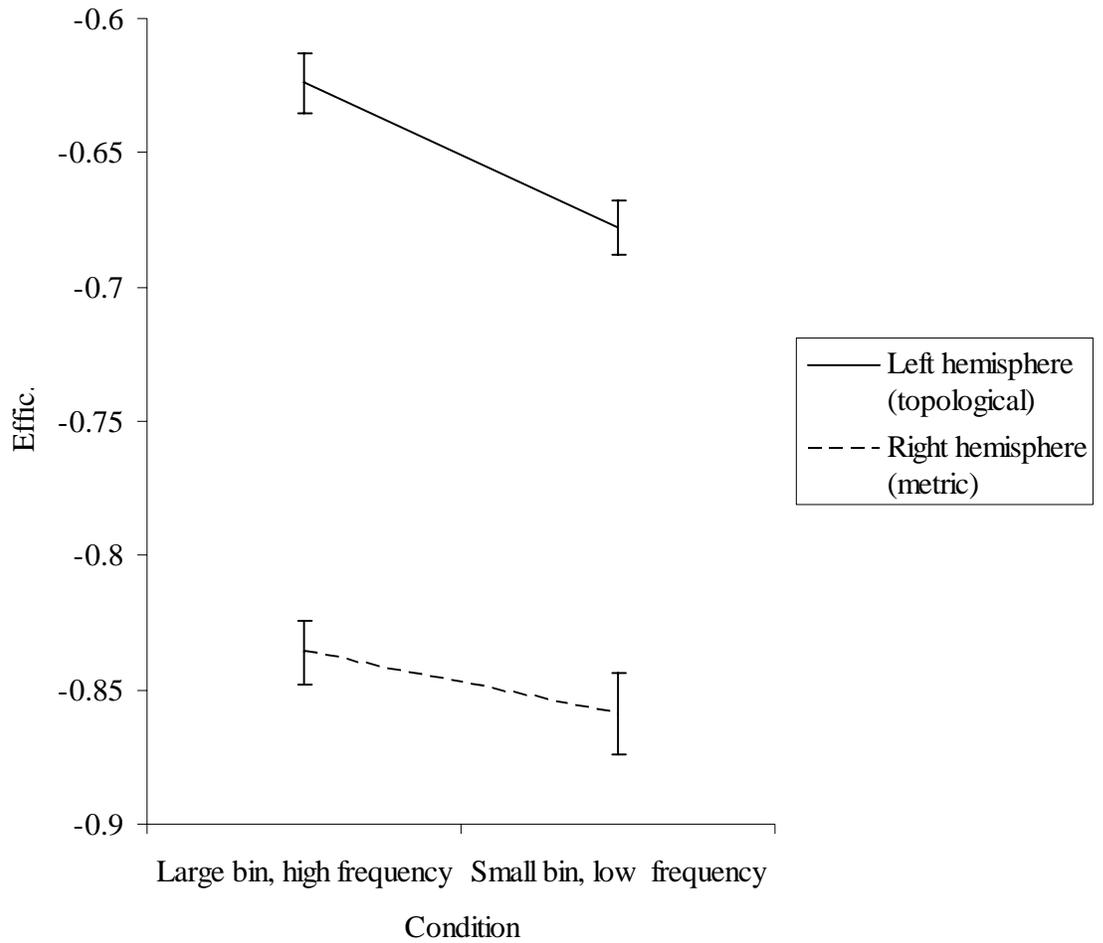


Figure 8. Log transform efficiency means for female participants in block 1 showing an interaction between hemisphere (task consistent) and condition (hemispherically inconsistent). Performance was generally better under large bin, high frequency conditions but proportionally better for the left hemisphere (topological task). Effic. = Transformed efficiency scores

differences across the conditions for the left hemisphere,  $t(34) = 8.102, p < .001$ , and for the right hemisphere,  $t(33) = 2.362, p = .024$  (Appendix L).

A marginally significant four-way interaction emerged,  $F(1, 32) = 3.583, p = .067$  and was attributable to a decrement in performance of the right hemisphere when judging distances under small bin, low frequency conditions. The assumption of consistency was examined in task x hemisphere interactions for each condition with alpha corrected for multiple comparisons to .01 (Bonferroni method). The only interaction to reach significance was in the large bin, low frequency condition,  $F(1, 32) = 6.455, p = .016$ . Although no significant hemisphere differences were noted for either task, the interaction showed better performance of the metric task by the right hemisphere compared to the left and better performance of the topological task by the left hemisphere compared to the right (Figure 9). The test of the assumption of inconsistency, a hemisphere (task consistent) x condition (hemispherically consistent) ANOVA, rendered no significant interaction but would have been of little interpretative value anyway because of the lack of consistency noted under small bin, high frequency conditions.

#### *Block 2.*

Block 2 was examined first for sex differences. With sphericity (Mauchley's) and equality of covariance (Box's M) assumed, a significant five-way interaction (sex x task x hemisphere x bin x frequency) was found,  $F(1, 55) = 4.844, p = .032$  so male and female participant data was examined separately. This interaction is likely attributable to the general emergence of the four-way interaction for female participants but no interactions at all for male participants [Appendix M].

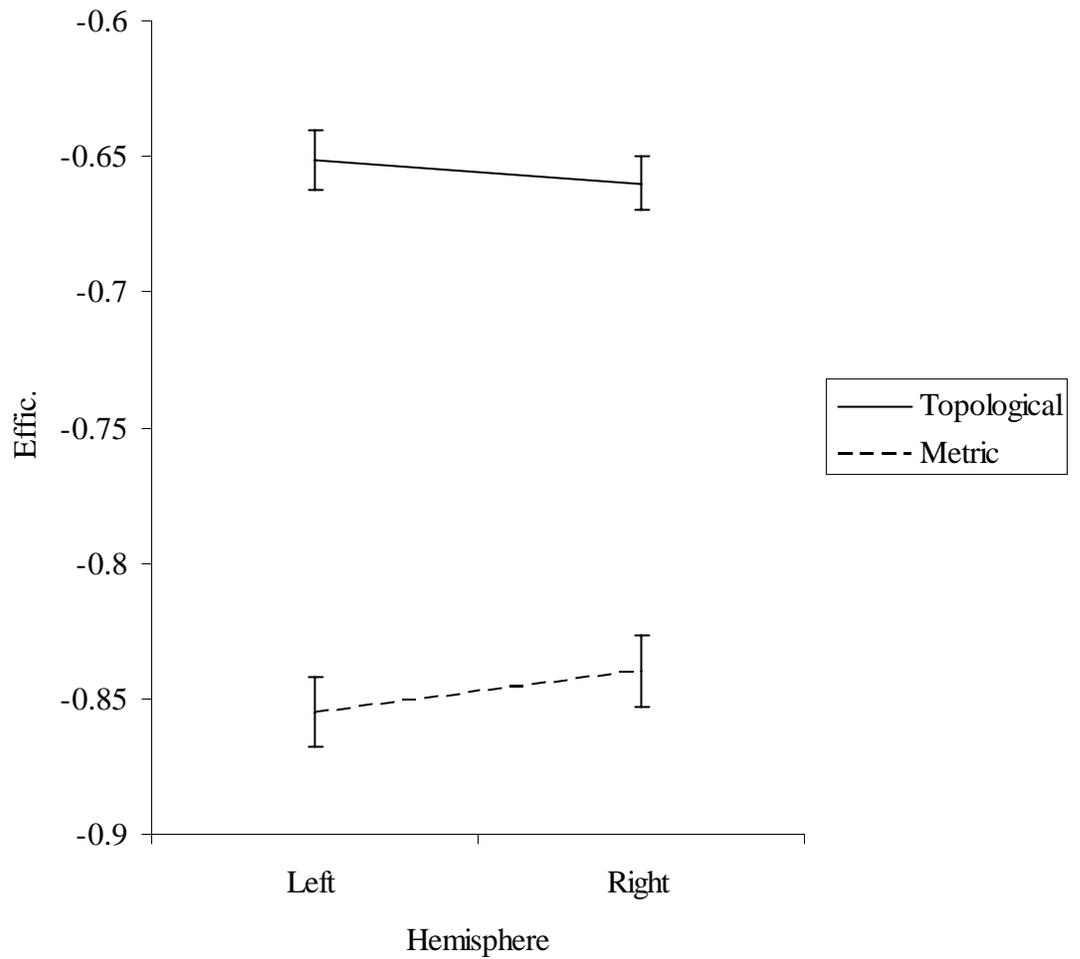


Figure 9. Log transform efficiency means for female participants in block 1 showing an interaction between task and hemisphere under large bin, low frequency conditions. The left hemisphere was more efficient than the right performing the topological task and the right hemisphere was more efficient than the left performing the metric task. Effic. = Transformed efficiency scores

### Male Participants

The test of the a priori hypotheses rendered a significant main effect of hemisphere (task consistent),  $F(1, 23) = 210.551, p < .001$  and of conditions (hemisphere inconsistent),  $F(1, 23) = 26.318, p < .001$ , showing better performance for the left hemisphere (topological task) than the right hemisphere (metric) and better performance under large bin, high frequency conditions than small bin, low frequency conditions but no significant interaction.

As well, no four-way interaction emerged for male participants. In fact, this analysis yielded only main effects for task,  $F(1, 21) = 191.554, p < .001$  with better performance in the topological task than the metric task, for bin,  $F(1, 21) = 25.227, p < .001$ , with better performance under large bin conditions than small bin conditions, and for frequency,  $F(1, 21) = 20.991, p < .001$ , with better performance under high frequency conditions than low frequency conditions [Appendix N]. Consistent with the lack of hemisphere effects in the four-way analysis, no task x hemisphere interactions were found for any conditions nor any hemisphere (task consistent) x conditions (hemispherically consistent).

### Female Participants

The hemisphere (task consistent) x condition (hemispherically inconsistent) analysis of the a priori hypotheses yielded a significant interaction (Figure 10),  $F(1, 34) = 7.576, p = .009$ , showing relatively better performance of the left hemisphere (topological task) under large bin, high frequency conditions ( $M = -0.587, SE = 0.013$ ) than small bin, low frequency conditions ( $M = -0.652, SE = 0.014$ ) compared to the right hemisphere (metric task) under large bin, high frequency conditions ( $M = -0.779, SE =$

0.011) and small bin, low frequency conditions ( $M = -0.814$ ,  $SE = 0.013$ ) and generally better performance under large bin, high frequency conditions, but proportionally better performance of the left hemisphere on the topological task under large bin, high frequency conditions (Appendix O).

The four-way analysis rendered a significant four-way interaction,  $F(1, 34) = 8.275$ ,  $p = .007$  and was attributable to a decrement in performance of the right hemisphere when judging distances under small bin, low frequency conditions and a marginal advantage of the left hemisphere when judging distances under large bin, high frequency conditions. The test of the assumption of consistency showed significant interactions under large bin, low frequency conditions,  $F(1, 34) = 12.297$ ,  $p = .001$ , and under small bin, high frequency conditions,  $F(1, 34) = 3.969$ ,  $p = .054$ . Under large bin, low frequency, the interaction showed better performance of the metric task by the right hemisphere than the left and better performance of the topological task by the left hemisphere than the right hemisphere as shown in Figure 11. Paired t-tests showed significant differences between the hemispheres on the topological task but not on the metric task. Similar results were found for the interaction under small bin, high frequency conditions with better performance of the metric task by the right hemisphere than the left and better performance of the topological task by the left hemisphere than the right but significant differences were not found across the hemispheres for either task (Figure 12). The task x hemisphere interaction was not significant under large bin, high frequency and small bin, low frequency conditions.

In the test of the inconsistency assumption, no significant interaction was noted between hemisphere (task consistent) and conditions (hemispherically consistent); that is

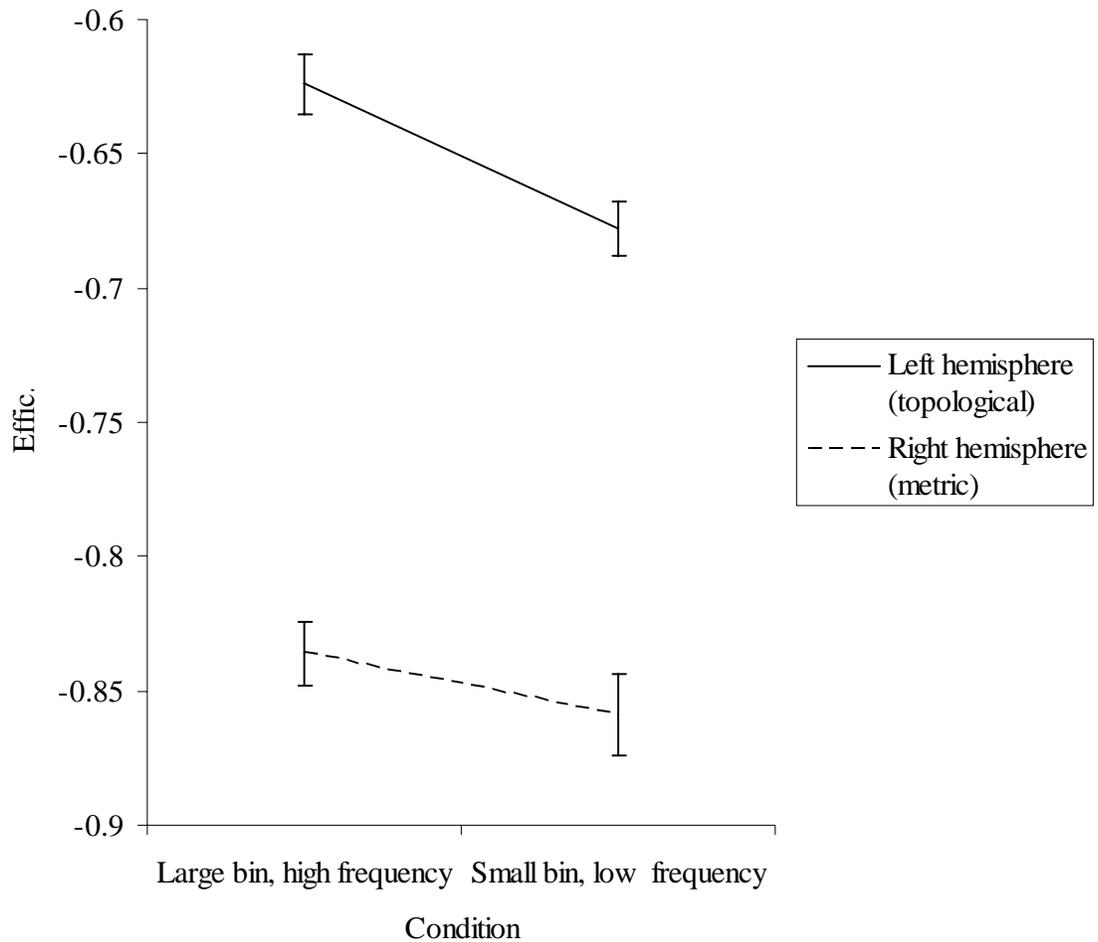


Figure 10. Log transform efficiency means for female participants in block 2 showing an interaction between hemisphere (task consistent) and condition (hemispherically inconsistent). Performance was better for the left hemisphere (topological task) and under large bin, high frequency conditions but proportionally better for the left hemisphere (topological task) under large bin, high frequency conditions. Effic. = Transformed efficiency scores.

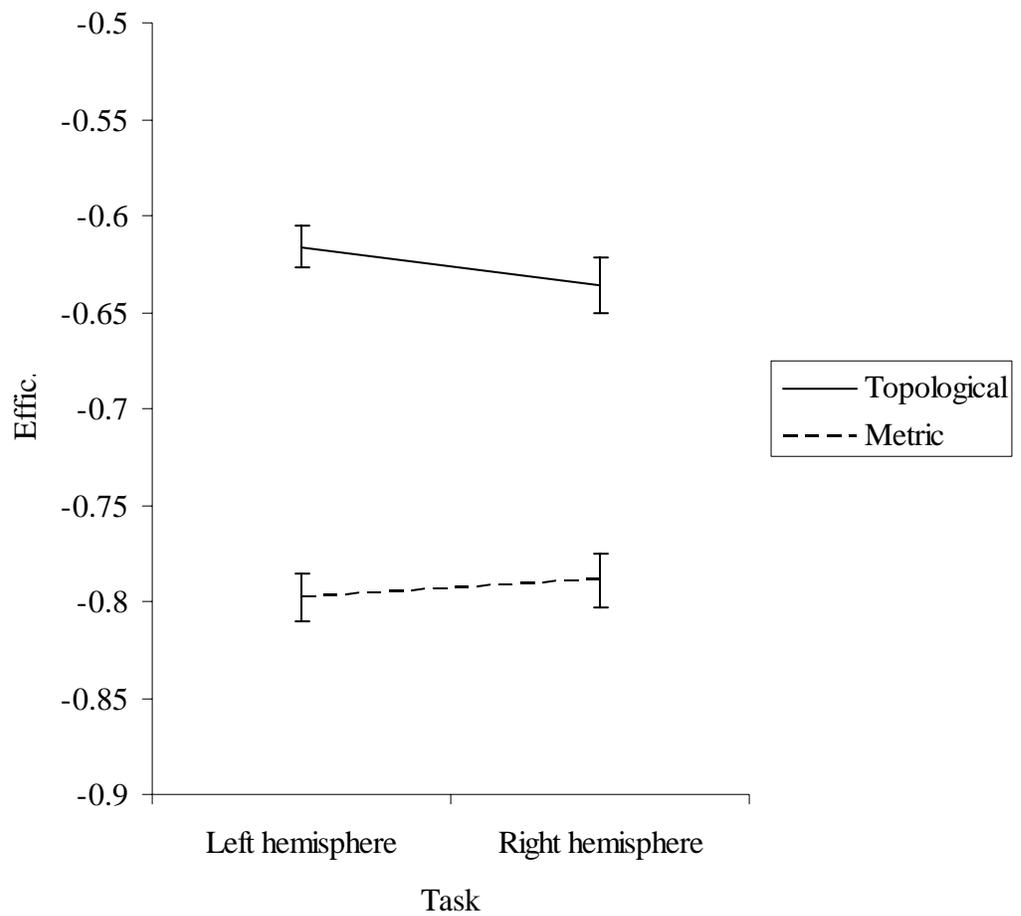


Figure 11. Log transform mean efficiency scores for female participants in block 2 under large bin, low frequency conditions for each task for each hemisphere. The task x hemisphere interaction shows better performance of the topological task by the left hemisphere and better performance of the metric task by the right hemisphere. Effic. = Transformed efficiency scores.

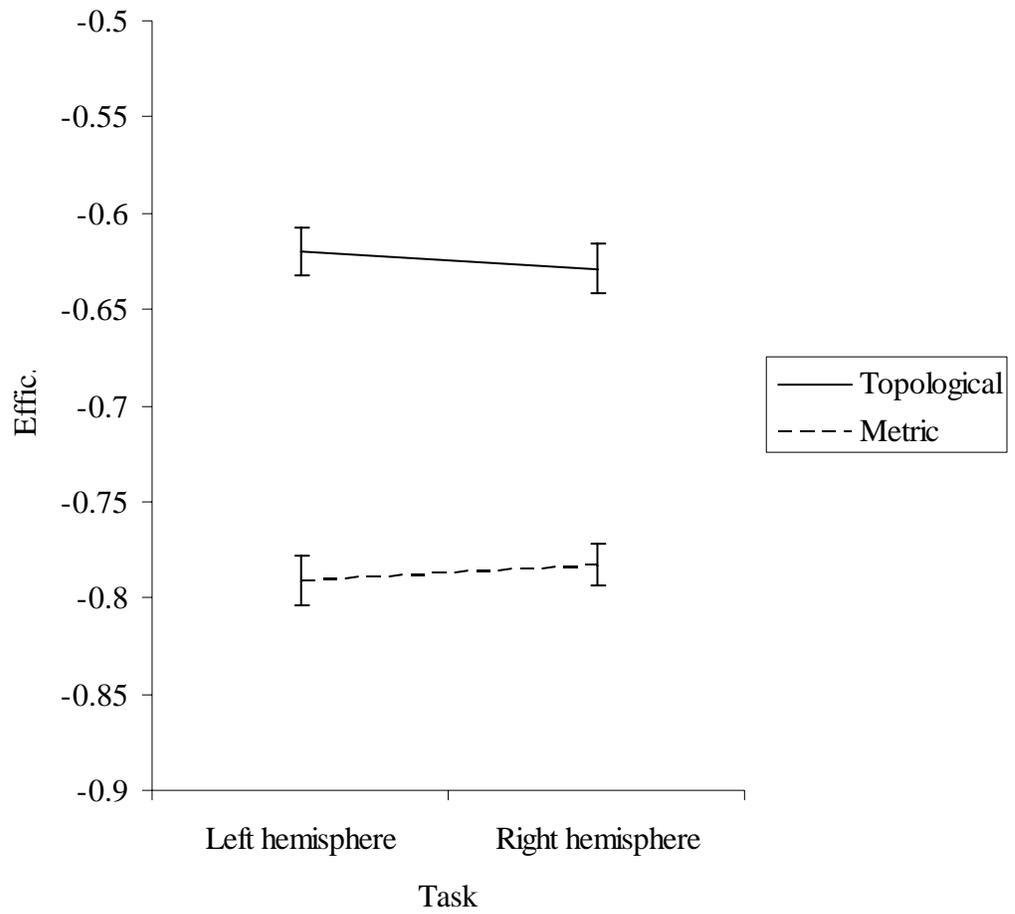


Figure 12. Log transform mean efficiency scores for female participants in block 2 under small bin, high frequency conditions for each task for each hemisphere. The task x hemisphere interaction shows better performance of the topological task by the left hemisphere and better performance of the metric task by the right hemisphere. Effic. = Transformed efficiency scores.

when task and hemisphere were consistent and bin and frequency were hemispherically consistent, no significant interaction was noted between hemisphere and condition.

### Discussion

The purpose of this experiment was to determine if the asymmetry noted for spatial judgments was attributable to asymmetry in attentional bins or asymmetry in spatial frequency processing. Bin theory predicted that the right hemisphere would perform the metric task more efficiently under large bin, high frequency conditions and the left hemisphere would perform the topological task more efficiently under small bin, low frequency conditions. Spatial frequency theory, on the other hand, predicted that the left hemisphere would perform the topological task more efficiently under large bin, high frequency conditions and the right hemisphere would perform the metric task more efficiently under small bin, low frequency conditions.

The double double dissociation method was developed to dissociate asymmetrically distributed input conditions when the tasks themselves are asymmetrically distributed. The double double dissociation, however, is only interpretable in the context of a four-way interaction and when the two underlying assumptions are met. In other words, bin theory and spatial frequency theory can be pitted one against the other when the double double dissociation emerges in the context of a left hemisphere advantage for the topological task and a right hemisphere advantage for the metric task and in the context of a left hemisphere advantage under small bin, high frequency conditions and a right hemisphere advantage under large bin, low frequency conditions. A right hemisphere advantage under large bin, low frequency conditions and a left hemisphere advantage under small bin, high frequency conditions

was not met for either male participants or female participants, nor was a left hemisphere advantage for the topological task and a right hemisphere advantage for the metric task found consistently. This interaction was only noted for female participants under large bin, low frequency and small bin, high frequency conditions..

The emergence of a sex difference was unanticipated. It is rarely examined, but has been reported at least once. Rybash and Hoyer (1992) reported that male participants were faster for the metric judgments and female participants were faster for topological judgments suggesting a functional asymmetry between male and female participants. In the present data, the sex difference is best characterized as a difference in hemisphere functioning where female participants processed the tasks under different conditions asymmetrically whereas male participants did not process the tasks asymmetrically under any conditions. For the purposes of clarity, the results from male and female participants will be considered separately.

### *Male Participants*

Perhaps most critical to the visual half field paradigm is unilateral processing. The complete lack of hemisphere effects for the male participants suggests that either the stimuli were bilaterally processed, or the hemispheres do not differ in the efficiency with which they perform the topological and metric tasks or with which they process large or small stimuli or high or low spatial frequency stimuli.

It is possible that male participants, unlike their female counterparts, were able to saccade to the stimulus or its afterimage and therefore process the stimuli bilaterally. Whether this is due to faster saccadic movement is not clear. Sex differences in speed of saccadic movements have not been investigated using eye tracking. However, one might

speculate about the possibility of a male advantage for eye tracking. Male participants are frequently reported to have an advantage for spatial processing and this has been associated with the evolutionary significance of spatial abilities for tracking. Hunting might be considered a skill that is enhanced by rapid eye tracking of target objects and so male participants would have an inherent advantage over female participants for rapid eye tracking. Alternatively, it might be that male participants have had increased exposure to video games requiring rapid target location, so that the musculature of their eyes has simply been trained to move more quickly. Information regarding exposure to this type of practice was not gathered but might represent a confound in visual half field studies.

Alternatively, although 150 ms presentation is commonly used by other investigators (Hellige & Michimata; Kosslyn et al., 1989c; Kosslyn et al., 1989c; Niebauer & Christman, 1998), the conditions of the present study might have served to increase the effective exposure duration of the stimulus. Effective exposure duration is the cumulative sum of the actual exposure duration of a stimulus and the temporal persistence of the afterimage (Jager & Postma, 2003). The presentation of white stimuli on black might have created an afterimage that was powerful enough to extend the effective exposure duration long enough to facilitate foveation and therefore bilateral processing (Wilkinson & Donnelly, 1999).

The single dissociation that emerged in the test of the a priori hypotheses in the first block showed better performance of the left hemisphere (topological task) under large bin high frequency conditions. This dissociation was attributable solely to improved performance of the topological task when attending to large areas of space and

when the stimulus was presented clearly; it cannot be attributed to any hemisphere effects. Furthermore, the large bin and high frequency advantage for making topological spatial judgments appears to be transient as no interaction was found for the second block of trials

### *Female Participants*

The double double dissociation predicted opposite patterns of performance under hemispherically inconsistent conditions. However, what emerged from the data for female participants across both blocks was a single dissociation. Similar to male participants in block 1, this single dissociation showed relatively better performance of the left hemisphere (topological task) under large bin, high frequency conditions.

Although marginal in the first block, four-way interactions emerged for female participants indicating hemispheric asymmetries for task, bin and frequency. The interaction was attributable to a decrement in performance for the right hemisphere when judging distances under small bin, low frequency conditions in both blocks. As well, the interaction in the second block was attributable to an additional advantage for the left hemisphere when judging distances under large bin, high frequency conditions. Consistency between task and hemisphere was found only under large bin, low frequency and small bin, high frequency conditions. The task x hemisphere effects showed better performance of the left hemisphere for the topological task but no hemispheric differences for the metric task. Generally, investigations of the task x hemisphere effect have yielded the opposite pattern of results showing only marginal hemisphere differences on the topological task but significant hemisphere effects for the metric task (Cowin & Hellige, 1994; Hellige & Michimata, 1989; Kosslyn et al., 1989;

Rybash & Hoyer, 1992). The right hemisphere advantage for the metric task did not emerge in the data at all despite having presented the stimuli at low luminance which has reportedly been the reason for the right hemisphere advantage for the metric task. (Kosslyn, et al. 1992, Experiment 4; Sergent, 1991).

A lack of right hemisphere advantage for the metric task has been previously attributed to exposure duration. Wilkinson and Donnelly (1999) examined both the topological and metric tasks at different exposure durations and noted that the right hemisphere advantage in the metric task only emerged at 100 ms exposure duration not at 200 ms exposure duration. Presenting the stimuli at 150 ms and not controlling for afterimage effects might have allowed for bilateral processing of the stimulus because of successful foveation to the actual image or to its aftereffect. Further to this, exposure durations longer than 120 ms have been reported to elicit a left hemisphere advantage (Sergeant, 1991).

The assumption of inconsistency held that large bin, low frequency is a right hemispherically consistent combination and small bin, high frequency is a left hemispherically consistent combination. No such dissociation was found here, so hemispheric consistency between large bin, low frequency and small bin, high frequency could not be confirmed. The lack of asymmetrical processing under large bin, low frequency and small bin, high frequency conditions even when the predicted task x hemisphere interaction was found suggests that consistency and therefore inconsistency in the combinations of bin and frequency cannot be confirmed. These findings suggest three possibilities. First, as with male participants throughout Experiment 1, the lack of hemisphere effects could be attributable to bilateral processing. That hemisphere effects

were found with task but not with condition suggests that either processing of bin size and frequency are more sensitive to the effects of bilateral processing than the processing of these tasks. Second, the combinations of bin size and spatial frequency under large bin, low frequency and small bin, high frequency are hemispherically inconsistent and lack of interaction is due to a cross-over effect for the hemispheres. In other words, the asymmetric predictions of one theory are incorrect. Third, it is also possible, however, that input characteristics are not asymmetrically processed and previously found hemispheric effects are driven by asymmetries in the processing of higher level tasks not by the way the hemispheres process stimulus characteristics. Kitterle, Hellige, and Christman (1992) have noted that asymmetries are not found in detection tasks but only in higher level cognitive tasks. Processing for input characteristics is presumed to be earlier in the processing sequence than make spatial judgments. Given this, asymmetries could be predicted to arise during the higher level tasks but not at the level of input characteristic processing.

Because task x hemisphere consistency could not be confirmed under large bin, high frequency or small bin, low frequency and because bin x frequency inconsistency could not be confirmed, the results from the test of the a priori hypotheses cannot be attributed to hemispheric differences in the processing of bin size or spatial frequency. Rather, these results might reflect a procedurally induced large bin or high frequency advantage. Indeed, main effects for frequency and bin were found in all data sets with advantages noted for high frequency and large bin. Two explanations for these effects are plausible. First, the advantage for high frequency could be attributed to effective exposure duration as longer durations facilitate the extraction of high spatial frequencies

(Bradshaw, Hicks & Rose, 1979; Pring, 1981; Sergent, 1982b, 1983b, 1987). Second, the main effect for bin showing a consistent advantage for large bin size might reflect task difficulty, with large bin judgments being easier than small bin judgments. The stimuli under large and small bin varied not only in size but also in terms of the shape of the reference point. For small bin, the reference point was a small straight line. For large bin, the reference point was a large circle. Conceivably, because of the shape of the circle, discriminations in conditions where the dot was very near the periphery of the circle would be more readily distinguishable even under blurred conditions.

The block effect was not surprising given that previous findings have suggested transience in the task x hemisphere interaction. Here, participants performed significantly more efficiently on the second block of trials suggesting a practice effect. How much practice is needed before a significant task x hemisphere interaction emerges is not clear however, given the possible increase in effortfulness of the task with the additional manipulations of bin and frequency.

Initially, three possible explanations for Kosslyn's effect were posed. The first explanation was that the task x hemisphere interaction noted previously (Cowin & Hellige, 1994; Hellige & Michimata, 1989; Kosslyn et al., 1989; Rybash & Hoyer, 1992) was attributable to the mediation of an attentional mechanism that relayed input to the hemisphere that was specialized for processing the size of the stimulus that facilitated task completion. The second explanation was that asymmetry in spatial judgments was due to asymmetry in processing spatial frequencies. The last and more complicated explanation was that both stimulus size and spatial frequency impacted performance on the two spatial judgment tasks. The results of the present study did not

unequivocally support any of these explanations because the task x hemisphere interaction did not emerge under large bin, high frequency and small bin, low frequency conditions and because the hemisphere (task consistent) x condition (hemispherically consistent) interaction did not emerge under large bin, low frequency and small bin, high frequency conditions. In other words, the task x hemisphere interaction emerged only under specific combinations of bin size and spatial frequency and, contrary to both bin theory and spatial frequency theory, these combinations cannot be characterized as hemispherically consistent.

The general lack of hemisphere effects found for male participants and inability to confirm bin x frequency inconsistency suggests the possibility that exposure duration was too long to facilitate asymmetrical processing for male participants. The purpose of the next study was to determine if 150 ms exposure duration facilitated bilateral processing.

## EXPERIMENT 2

This experiment was intended to determine whether the paucity of hemisphere effects noted in Experiment 1 could be attributed to stimulus presentation conditions, namely exposure duration. The lack of hemisphere effects for male participants and the lack of hemisphere (task consistent) x condition (hemispherically consistent) interaction for the female participants suggested that the tasks might have been processed bilaterally by male participants and that input characteristics might have been processed bilaterally for female participants when stimuli were presented at 150 ms exposure duration.

The exposure duration at which stimuli were presented might also account for the systematic left hemisphere advantage/right hemisphere disadvantage found in the test of the double double dissociation. If participants were able to saccade to the stimulus within 150 ms or within the period of time in which an afterimage remained on the computer screen, the stimuli would be processed by foveal regions of the retina, regions with typically smaller receptive fields tuned to process higher spatial frequencies. Spatial frequency theory would predict a left hemisphere advantage and right hemisphere disadvantage under these conditions. It is possible that, under the present experimental procedures, by presenting the stimuli for 150 ms, a systematic left hemisphere advantage or right hemisphere disadvantage was established. The hemisphere effects noted in the double double dissociation might then be attributed to differences in the efficiency of processing high spatial frequency.

The purpose of Experiment 2 was to determine whether participants were able to foveate to the laterally presented stimulus at 150 ms. If participants are able to saccade to the stimulus, bilateral processing of the stimulus is possible and unilateral processing

of the stimuli in Experiment 1 cannot be guaranteed. Bilateral processing could result in a general loss of hemisphere effects or a loss specific to either task, bin size or spatial frequency assuming variable thresholds for bilateral processing. If participants are not able to saccade to the stimulus, unilateral processing can be assumed.

## Method

### *Participants*

Nineteen participants from the undergraduate psychology participant pool began testing. Three participants could not be successfully calibrated to the eye-tracking machine because of interference from luminescent cosmetics. Three data sets were excluded from the final sample due to computer recording errors. All participants except one were strongly right-handed using the same criteria as in Experiment 1. The participant that was not strongly right-handed was, in fact, strongly left-handed, and was excluded from the final sample. The final sample consisted of 12 participants (4 male participants, 8 female participants). Mean age of the sample was 20.92 years ( $SD = 5.53$ ; range – 17 to 37 years).

### *Stimuli*

The SensoMotoric eye tracker hardware has a memory storage capacity that is limited to a maximum of 250 trials for each participant. To accommodate these limitations, the number of trials was reduced. The stimuli used were identical to 16 of the stimuli used in Experiment 1. The 16 stimuli consisted of 8 large bin and 8 small bin stimuli with four of each type presented under high frequency conditions and 4 under low frequency conditions. Only four dot positions were used, two above and two below

the bar or circle and these positions varied in the distance they were placed from the bar or circle.

Participants again completed 2 blocks with each block including a set of trials for the topological task and a set of trials for the metric task. Each set consisted of 32 trials. Within each set, all 16 stimuli were presented in the right visual field and 16 in the left visual field. Stimuli were presented sequentially under low luminance conditions, approximately 4 cd/m<sup>2</sup>, on a 19 inch Sceptre monitor with a resolution of 1024 x 768 pixels which refreshed at 65 Hz.. Eye movement was detected using a RED II eye tracker from SensoMotoric Instruments and recorded using iView software.

### *Procedure*

The testing conditions simulated Experiment 1 in all respects. After giving informed consent, participants completed the handedness questionnaire [Appendix B] and were briefed about the eye tracking camera. Participants were then asked to remain motionless with their chins secured by a chin rest positioned 57 cm from and directly in front of the horizontal middle of the screen. A 9 point calibration procedure followed to ensure that valid data could be gathered. The iView eye tracker is accurate to within 0.5 degrees of arc.

### Results

Mean values for time zero were calculated for each visual field across all conditions. Using 512 (pixel number at central fixation) as the test value, one-sample t-tests showed significant deviation from central fixation for all conditions with deviations being consistently left of centre at time zero. To account for this, difference scores were calculated for each participant for each condition. Each difference score represented the

distance moved from each individual's fixation to the pixel at which their eyes were directed at 100, 117 and 150 ms. Any value exceeding 2.5 standard deviations from each variable mean was excluded as an outlier.

All variables were initially entered into a 2 (block: 1 and 2) x 2 (task: metric and topological) x 2 (hemisphere: right and left) x 2 (bin: large and small) x 2 (frequency: high and low) x 3 (exposure time: 100 ms, 117 ms, and 150 ms) repeated measures ANOVA. Because of the small number of male participants, the data were not examined for sex differences. A main effect for block was found,  $F(1, 11) = 22.906, p = .001$ , showing significantly further distances traveled leftward in the second block [Appendix P]. For this reason, the blocks were analyzed separately.

Difference scores were averaged across conditions and tasks for each hemisphere for each exposure time. Using one-sample t-tests, these averaged difference scores were tested against a value of 93.8 pixels for right visual field presentations and -93.8 for left visual field presentations, 93.8 pixels being the distance between fixation and the innermost edge of the stimulus presented in each visual field. For the right visual field, an average difference score significantly less than 93.8 represents a successful unilateral presentation whereas a value equal to or significantly greater than 93.8 represents a saccade to or beyond the stimulus. For the left visual field, an average difference score significantly larger than 93.8 represents a successful unilateral presentation whereas a value equal to or significantly less than 93.8 represents a saccade to or beyond the stimulus.

### *Block 1*

At 150 ms, participants were able to saccade leftward to the stimulus,  $t(11) = 0.145$ ,  $p = .888$ , with a mean distance traveled of 92.5 pixels ( $SD = 30.8$ ) and rightward to a point significantly beyond the stimulus,  $t(11) = 2.576$ ,  $p = .026$ , with a mean distance traveled of 121.8 pixels ( $SD = 37.7$ ). At 117 ms, mean distance traveled fell significantly short of the test value for both leftward movement,  $t(11) = 5.155$ ,  $p < .001$ , ( $M = -53.4$ ,  $SD = 27.2$ ) and rightward movement,  $t(11) = -4.000$ ,  $p = .002$ , ( $M = 64.3$ ,  $SD = 25.5$ ). However, the test value fell within 2 standard deviations of each mean. For each direction, one participant was able to saccade beyond 93.8 pixels. At 100 ms, no participants were able to saccade to the stimulus as indicated by means falling significantly short of the test value and beyond 2  $SD$ s for both leftward and rightward movement,  $t(11) = 9.294$ ,  $p < .001$ , ( $M = -32.8$ ,  $SD = 22.7$ ) for leftwards and  $t(11) = -10.938$ ,  $p < .001$ , ( $M = 39.1$ ,  $SD = 17.3$ ) for rightwards movement (Figure 13 and 14; Appendix P).

### *Block 2*

At 150 ms, participants were able to saccade rightward to the stimulus,  $t(11) = 1.629$ ,  $p = .132$ , with a mean distance traveled of 107.2 pixels ( $SD = 28.6$ ) and leftward significantly beyond the stimulus,  $t(11) = -3.691$ ,  $p = .004$ , with a mean distance traveled of -127.3 ( $SD = 31.4$ ). At 117 ms, mean distance traveled rightward and leftward fell significantly short of the test value,  $t(11) = -4.334$ ,  $p = .001$ , ( $M = 65.2$ ,  $SD = 22.9$ ) and  $t(11) = 2.973$ ,  $p = .013$  ( $M = -67.8$ ,  $SD = 30.3$ ) respectively. However, the test value fell within two standard deviations for both rightward and leftward movement. In fact, two participants successfully saccaded beyond the stimulus going leftward and one

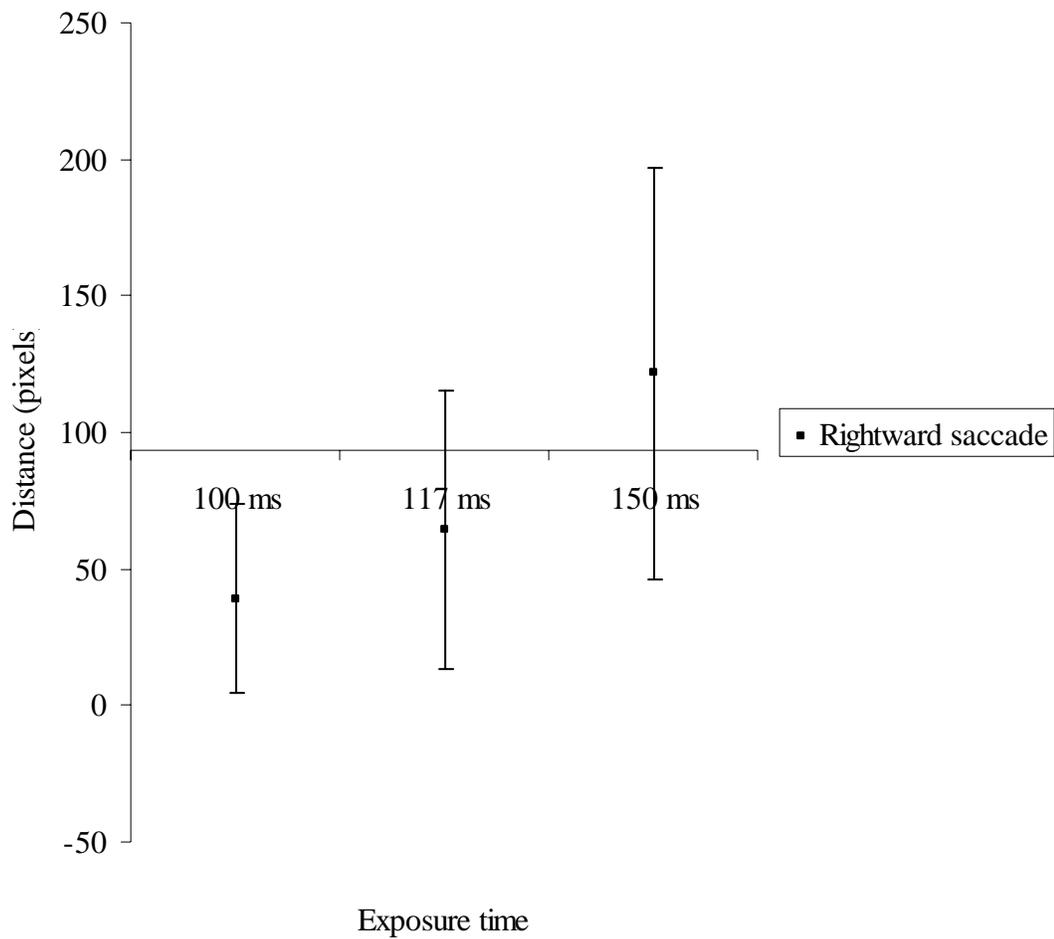


Figure 13. Block 1 mean distance ( $2SD$ ) for rightward saccades toward stimuli presented to the left hemisphere for 100, 117 and 150 ms exposure durations showing eye movement sufficient to reach the stimulus at 150 and 117 ms exposure durations but not at 100 ms exposure duration. The vertical axis represents the distance from central fixation (0) to the stimulus (93.8 pixels) with measurements taken at 100, 117 and 150 ms indicated on the horizontal axis. ms = milliseconds

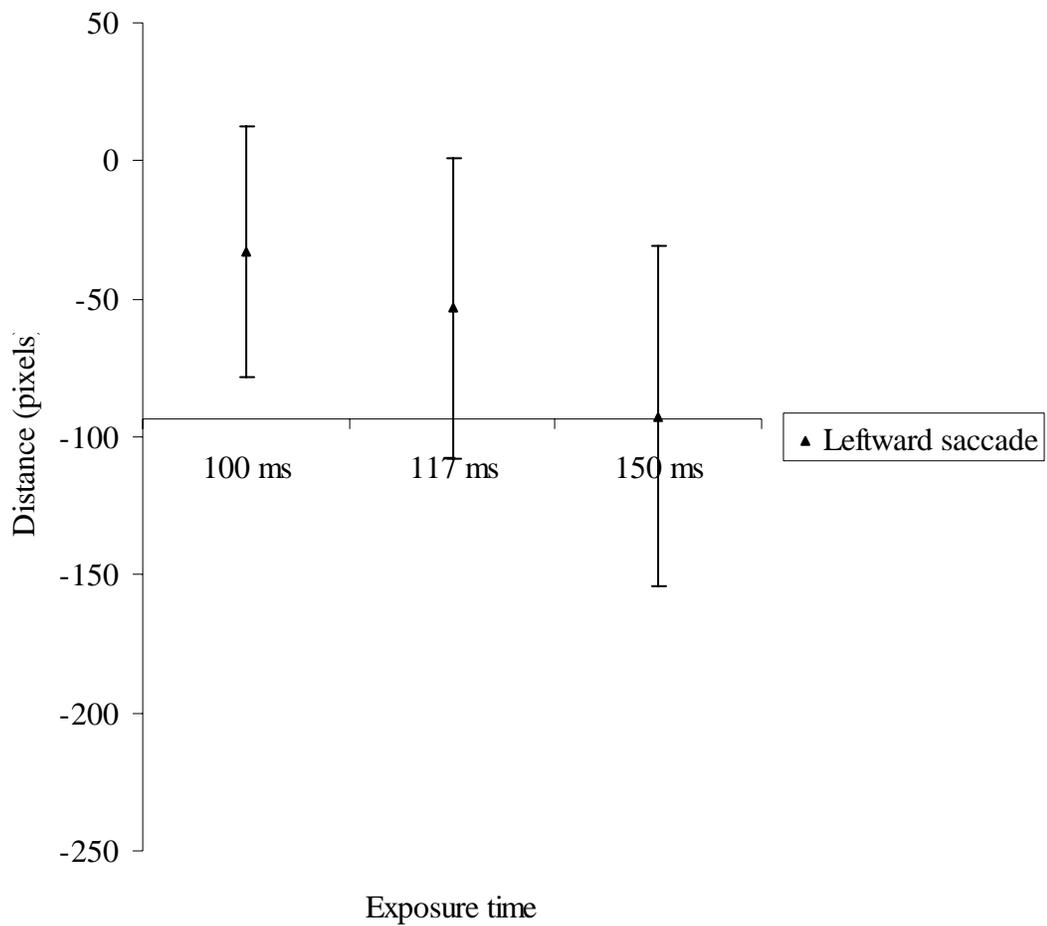


Figure 14. Block 1 mean distance ( $2SD$ ) for leftward saccades toward stimulus presented to the right hemisphere for 100, 117 and 150 ms exposure durations showing eye movement sufficient to reach the stimulus at 150 and 117 ms exposure durations but not at 100 ms exposure duration. The vertical axis represents the distance from central fixation (0) to the stimulus (93.8 pixels) with measurements taken at 100, 117 and 150 ms indicated on the horizontal axis. ms = milliseconds

participant saccaded beyond the stimulus going rightward. At 100 ms, mean distance traveled fell significantly short of the test value going both rightward and leftward,  $t(11) = -9.958, p < .001, (M = 42.2, SD = 18.0)$  and  $t(11) = 6.879 (M = -4.05, SD = 26.9)$  respectively. Only one participant was able to saccade leftwards 95.4 pixels on average at 100 ms (Figures 15 and 16; Appendix P).

### Discussion

The purpose of this experiment was to determine whether participants were able to foveate and therefore bilaterally process stimuli presented at 150 ms. These results showed that in each visual field participants were able to saccade to and even past the point at which the stimulus would be presented within 150 ms. That participants saccaded further than 3.75 visual angles at 150 ms suggests that participants were in the midst of a search for the stimulus. In other words, at 150 ms, participants were likely overshooting the stimulus. If this is the case, participants clearly were capable of foveal viewing of the stimulus at 150 ms.

It is possible then that the lack of hemisphere effects for the male participants and the violation of the assumption of inconsistency for the female participants could be attributable to bilateral viewing. Evidently, 150 ms exposure duration was too long to ensure unilateral presentation. Nor was 117 ms brief enough to ensure unilateral presentation in both directions and both blocks for all participants. These findings raise considerable doubts regarding the interpretation of previous work that has utilized reaction times of 150 ms (Hellige & Michimata; Kosslyn et al., 1989c; Kosslyn et al. 1989c; Niebauer & Christman, 1998) and 120 ms (Sergent, 1982b). The hemisphere effects noted in these studies might well be attributed to an artifact in the speed of,

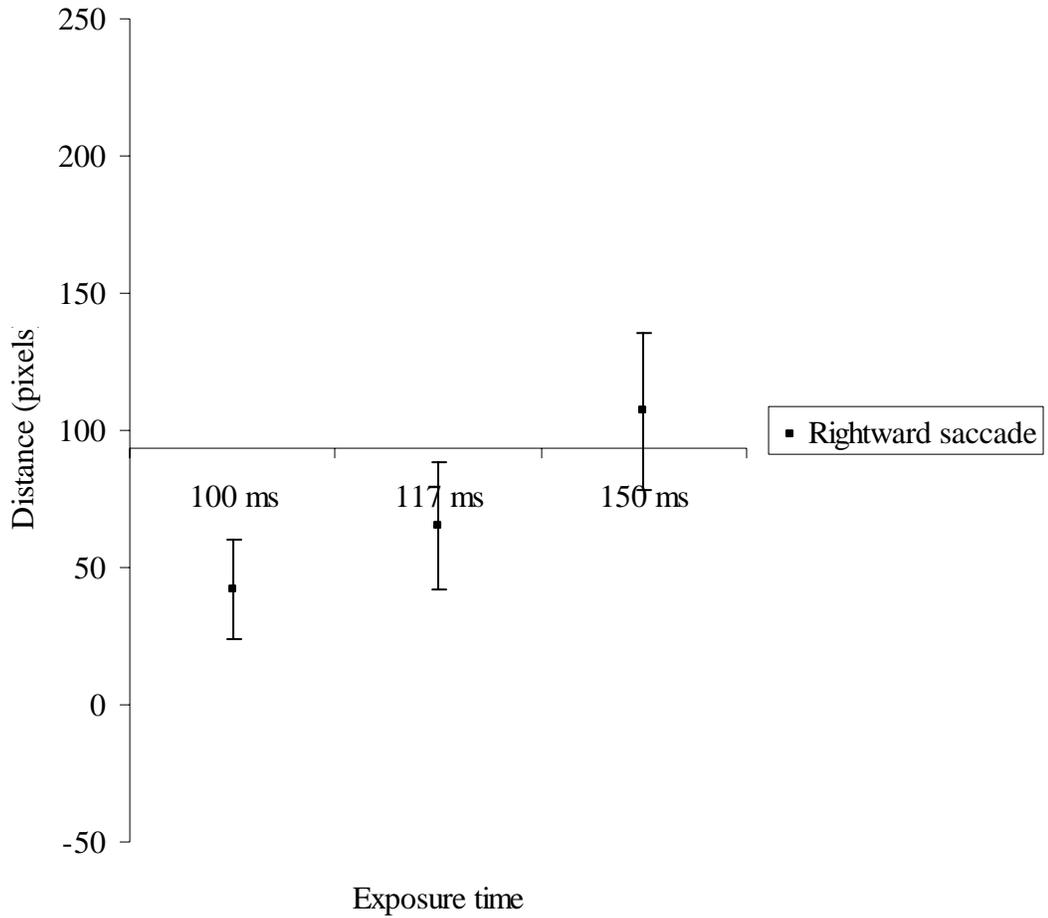


Figure 15. Block 2 mean distance ( $2SD$ ) for rightward saccades toward stimulus presented to the left hemisphere for 100, 117 and 150 ms exposure durations showing eye movement sufficient to reach the stimulus at 150 exposure durations but not at 100 or 117 ms exposure duration. The vertical axis represents the distance from central fixation (0) to the stimulus (93.8 pixels) with measurements taken at 100, 117 and 150 ms indicated on the horizontal axis. ms = milliseconds

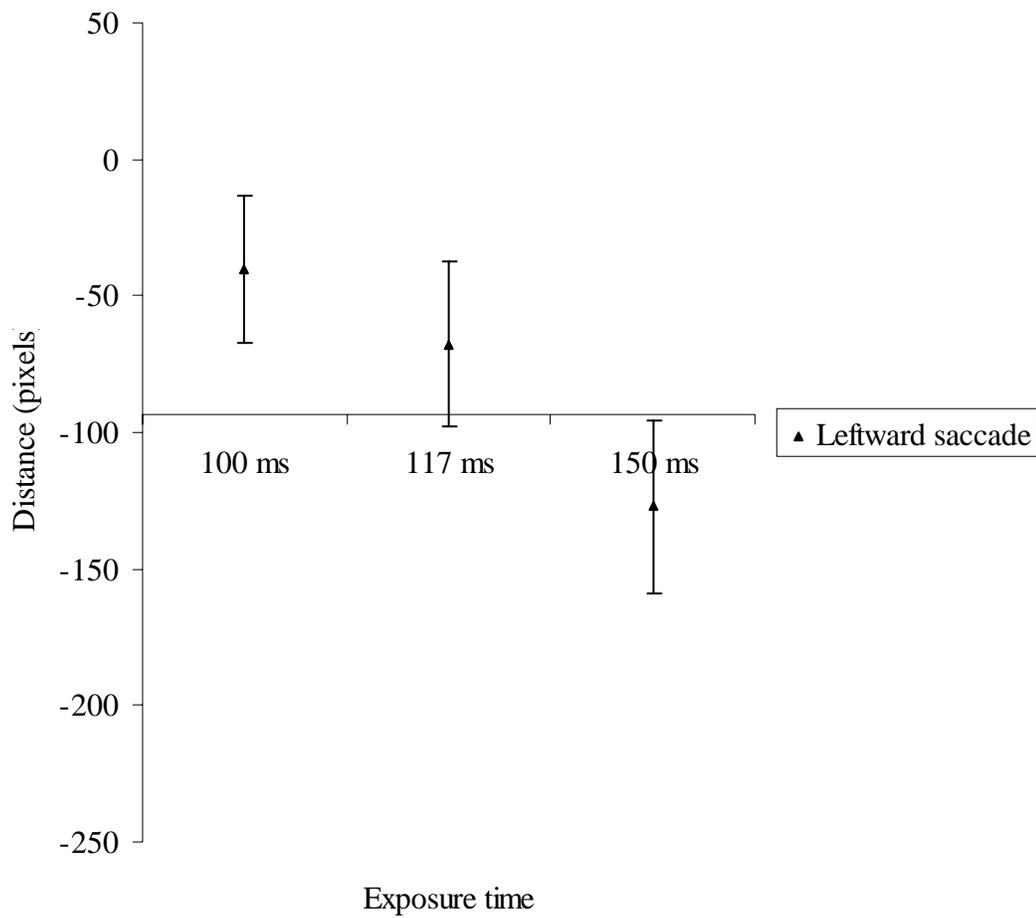


Figure 16. Block 2 mean distance ( $2SD$ ) for leftward saccades toward stimulus presented to the right hemispheres for 100, 117 and 150 ms exposure durations showing eye movement sufficient to reach the stimulus at 150 and 117 ms exposure durations but not at 100 ms exposure duration. The vertical axis represents the distance from central fixation (0) to the stimulus (93.8 pixels) with measurements taken at 100, 117 and 150 ms indicated on the horizontal axis. ms = milliseconds

saccadic movement. Faster saccades result in faster responding which would give the illusion of asymmetrical processing for the task when the difference in response time is attributable only to differences in saccadic speed. The results presented in Figures 13 through 16 suggest that initially participants were able to saccade further rightward in 150 ms than leftward but with practice, participants developed a leftward saccadic bias. This suggests that the right hemisphere advantage typically observed for the metric task could be due to faster leftward saccadic movement rather than asymmetry in processing of metric spatial relations.

At 100 ms, saccadic movement fell significantly short of the stimulus location in both visual fields ensuring unilateral presentation to each hemisphere. Given this, exposure time must be reduced in order to ensure unilateral presentation. In the next experiment, exposure duration of the stimulus is reduced and afterimages controlled in order to facilitate unilateral viewing. Under unilateral viewing conditions, hemisphere effects should emerge for male participants and for female participants, a right hemisphere advantage and a hemisphere (task consistent) x condition (hemispherically consistent) interaction should be noted for the metric task.

### EXPERIMENT 3

The interpretability of results from the visual half field paradigm depends on the assurance that stimuli were presented unilaterally. With no hemisphere effects emerging for male participants and no hemisphere effects emerging in the test of the presumably consistent combinations of bin and frequency in Experiment 1, the possibility that stimuli were being processed bilaterally was examined. In Experiment 2, participants were clearly able to saccade the distance between central fixation and the location of the stimulus at 150 ms. Exposure duration had to be reduced to 100 ms before a 2 *SD* range around mean distance saccaded fell short of stimulus presentation.

Clearly, reducing exposure duration will facilitate unilateral viewing. However, consideration of the effect of afterimages is also needed. Afterimages are a common problem in computerized presentation of visual stimuli. They arise not only from the traces of stimulation coursing through the visual system but also from residual radiant energy from the computer screen itself. The problem with afterimages is that they effectively increase presentation time because, if conditions are conducive, participants can perform tasks based upon afterimage input rather than the input from the stimulus itself. As a consequence, even though participants cannot bilaterally process the stimulus itself, the afterimage persists long enough to facilitate foveal processing and therefore bilateral processing of the afterimage. In other words, even though the stimulus is presented at a duration short enough to prevent bilateral viewing, the afterimage might be powerful enough to result in an effective exposure duration much longer than intended.

Masking is the most obvious way to prevent this, but surprisingly, others have

not typically masked their stimuli. One of the difficulties with masking when testing input characteristics is that the mask itself can impact the processing of input characteristics such that hemispheric asymmetries can be attributed to the presentation conditions of the mask rather than the stimulus. To this end, a mask should be designed to be as consistent with critical input characteristics as possible. Perhaps the most obvious way to create an effective mask would be to use a master stimulus that is the same as the test stimulus without the variation required of the task manipulation. This strategy was initially tried and tested on two lab colleagues. It was found to produce such powerful interference that responding was no better than chance. For this reason, a plain contrast grating closely matching the dimensions of the stimulus was used with the spatial frequency of the grating set to match the spatial frequency of the stimulus.

In this study, the same procedures as those presented in Experiment 1 were employed except that stimulus presentation was reduced to 100 ms and a 100 ms mask was used to prevent processing of the afterimage. It is anticipated that with unilateral viewing, hemisphere effects will be noted for male participants and a hemisphere (task consistent) x condition (hemispherically consistent) interaction will emerge for female participants.

## Method

### *Participants*

The experimental group consisted of thirty participants (16 male participants, 14 female participants). Participants were students who received course credit for participating. Ages ranged from 19 to 35 with a mean age of 22.5 ( $SD = 3.62$ ). Using the same procedures as those employed in Experiment 1, handedness was assessed. All

participants in the experimental group were rated as strongly right-handed. The control group consisted of thirty participants randomly selected from the pool of participants tested in Experiment 1. One-way analysis of variance showed no significant differences between the groups on age or handedness. No difference in proportion of male participants and female participants between the groups was noted either (Mann-Whitney).

### *Stimuli*

The stimuli were the same as those used in Experiment 1. Immediately after presentation of the stimulus, a mask was applied. The mask was a grating consisting of 12 white lines each line being 3 pixels wide and 122 pixels long (Appendix Q).

### *Procedure*

All procedures and experimental conditions were identical to those used in Experiment 1 except that the stimuli were presented for only 100 ms instead of 150 ms and were followed immediately by a mask. The masks were presented at the same spatial frequency as the stimulus for 100 ms.

## Results

All data were analyzed on a Pentium III IBM compatible PC using E-Prime, Microsoft Excel or Statistical Package for Social Science software. Spoiled trials were eliminated. Each participant's data set was checked for outliers using the same procedure as in Experiment 1. In other words, means and standard deviations for each task in each block were calculated and any data points that fell beyond 2 *SD* from the mean for each task for each block were deemed to be outliers. All data were then

averaged for each participant for each condition defined by block, task, hemisphere, bin size and frequency [Appendix R].

### *Preliminary Analyses*

Before proceeding to an analysis of exposure duration effects and the a priori hypotheses, the data were examined for speed/accuracy trade-offs and normality.

#### *Reaction time and accuracy.*

Significant correlations between reaction time and accuracy were noted for both tasks. Speed/accuracy trade-offs were evident for the metric task, and for the topological task, longer response times correlated with more errors (Tables 6 and 7). To account for co-linearity, efficiency scores were calculated by dividing reaction time into percent correct and multiplying by 100. Efficiency scores falling more than two standard deviations from the mean were eliminated from the data set.

#### *Normality.*

Deviation from normality (Shapiro-Wilks) was examined for each exposure duration group [Appendix S]. A single significantly non-normal distribution was noted for the 150 ms exposure duration group with the distribution for topological, left hemisphere, large bin, high frequency in block 1 showing a mild positive skew. For the 100 ms exposure duration group, two non-normal distributions were found in the second block. The distribution for the metric task, right hemisphere under large bin, high frequency condition showed a well-defined positive skew and leptokurtotic rise while the distribution for the metric task, right hemisphere, small bin, high frequency condition showed only a slight positive shift. Because these variables were critical to the

double double dissociation and its assumptions,  $\log^{10}$  transforms on the efficiency scores were

Table 6

*Correlation Coefficients for Reaction Time and Accuracy for the Topological*

*Conditions (n = 60)*

Condition			Block 1	Block 2
Hemisphere	Bin size	Frequency		
1. right	large	high	-.206	-.053
2.		low	-.123	-.084
3.	small	high	-.443**	-.195
4.		low	-.332**	-.123
5. left	large	high	-.078	-.013
6.		low	.195	-.250
7.	small	high	-.305*	-.442**
8.		low	-.512**	-.216

\* $p < .05$ ; \*\* $p < .001$

Table 7

*Correlation Coefficients for Reaction Time and Accuracy for the Metric Conditions (n = 60)*

Condition			Block 1	Block 2
Hemisphere	Bin size	Frequency		
1. right	large	high	.109	.205
2.		low	.035	.311*(p = .016)
3.	small	high	-.082	.061
4.		low	-.110	.010
5. left	large	high	.046	.293*(p = .023)
6.		low	.063	.274*(p = .034)
7	small	high	.095	.189
8.		low	.028	.079

\*p < .05

computed and all subsequent analyses performed on the  $\log^{10}$  transforms.

### *Between Subjects*

All log transformed variables were entered into a 5 within (block, task, hemisphere, bin and frequency) x 2 between (exposure duration, sex) repeated measures ANOVA. A significant main effect for block was found,  $F(1, 40) = 311.022, p < .001$ . Mean comparisons showed significantly better efficiency for all pairs in the second block. As well, a block x task x bin x exposure duration x sex interaction was found,  $F(1, 40) = 8.728, p = .005$ , so the data were divided by block and male participants and female participants were examined separately for differences between exposure duration [Appendix T]. Four within (task x hemisphere x bin x frequency), 1 between (exposure duration) repeated measures ANOVAs were conducted for block 1 male participants, block 1 female participants, block 2 male participants and block 2 female participants.

#### *Block 1.*

##### Male Participants

In the between groups test of the a priori hypotheses, no interaction was found. Likewise, exposure duration had no effect on any of the factors in the five-way (task x hemisphere x bin x frequency within and exposure duration between). Reduced exposure duration did not elicit any task x hemisphere interactions nor any hemisphere (task consistent) x condition (hemispherically consistent) interactions but did result in significantly poorer performance in general,  $F(1, 20) = 1476.234, p < .001$  with means indicating better performance under 150 ms exposure duration ( $M = -0.752, SE = 0.031$ ) compared to 100 ms exposure duration ( $M = -0.778, SE = 0.025$ ) [Appendix U].

## Female Participants

In the between groups test of the a priori hypotheses, exposure duration did not vary a significant hemisphere (task consistent) x condition (hemispherically inconsistent) interaction,  $F(1, 28) = 17.226, p = .001$ . Figure 17, however, shows an interaction between exposure duration and condition,  $F(1, 28) = 8.523, p = .007$  (Appendix V). A greater decrement in efficiency was noted for small bin, low frequency conditions than for large bin, high frequency conditions when exposure duration was reduced ( $M = -.808, SE = 0.022$  and  $M = -.734, SE = 0.023$  respectively) compared to small bin, low frequency and large bin, high frequency conditions with exposure duration of 150 ms ( $M = -.756, SE = 0.018$  and  $M = -.728, SE = 0.019$  respectively). No five-way interaction (task x hemisphere x bin x frequency within and exposure duration between) emerged, but exposure duration had a significant effect on the performance of the tasks under different bin sizes,  $F(1, 28) = 9.184, p = .005$ . At 150 ms, both tasks were performed less efficiently under small bin conditions compared to large bin conditions but at 100 ms, the topological task was performed more efficiently under large bin and significantly less efficiently under small bin conditions. At 100 ms, the metric task was performed less efficiently under both large bin and small bin conditions. Figure 18 demonstrates this three-way interaction graphically. As well, exposure duration had a significant effect on how efficiently the hemispheres processed frequency,  $F(1, 28) = 5.302, p = .029$ . This interaction showed that the left hemisphere advantage over the right hemisphere for high spatial frequency at 150 ms dissipated with reduced exposure duration. The right hemisphere advantage over the left for low spatial frequency at 150 ms was reversed when exposure duration was reduced. This is shown

in Figure 19. No task x hemisphere interactions were found nor did reducing exposure duration elicit any task x hemisphere interactions. The between-groups test of the assumption of inconsistency showed at 100 ms an exaggeration of the effect shown at 150 ms. This effect demonstrated better performance by the left hemisphere (topological task) under large bin, low frequency conditions and better performance by the right hemisphere (metric task) under small bin, high frequency conditions, but because consistency between task and hemisphere could not be confirmed, this interaction cannot be interpreted as support for consistency between bin and frequency.

### *Block 2.*

#### Male Participants

A significant three-way interaction between exposure duration, hemisphere (task consistent) and condition (hemispherically inconsistent) was found,  $F(1, 22) = 4.395$ ,  $p = .048$  [Appendix W]. At 150 ms, the left hemisphere (topological task) outperformed the right hemisphere (metric task) under both large bin, high frequency conditions ( $M = -.584$ ,  $SE = 0.029$  and  $M = -.769$ ,  $SE = 0.029$  respectively) and under small bin, low frequency conditions ( $M = -.610$ ,  $SE = 0.027$  and  $M = -.792$ ,  $SE = 0.035$  respectively). With reduced exposure duration, the right hemisphere's (metric task) performance was mildly better under small bin, low frequency ( $M = -.780$ ,  $SE = 0.027$ ) than large bin, high frequency ( $M = -.786$ ,  $SE = 0.023$ ) and the left hemisphere's performance improved marginally under large bin, high frequency conditions ( $M = -.574$ ,  $SE = 0.023$ ) and worsened considerably under small bin, low frequency conditions ( $M = -.648$ ,  $SE = 0.021$ ). Figure 20 depicts this effect.

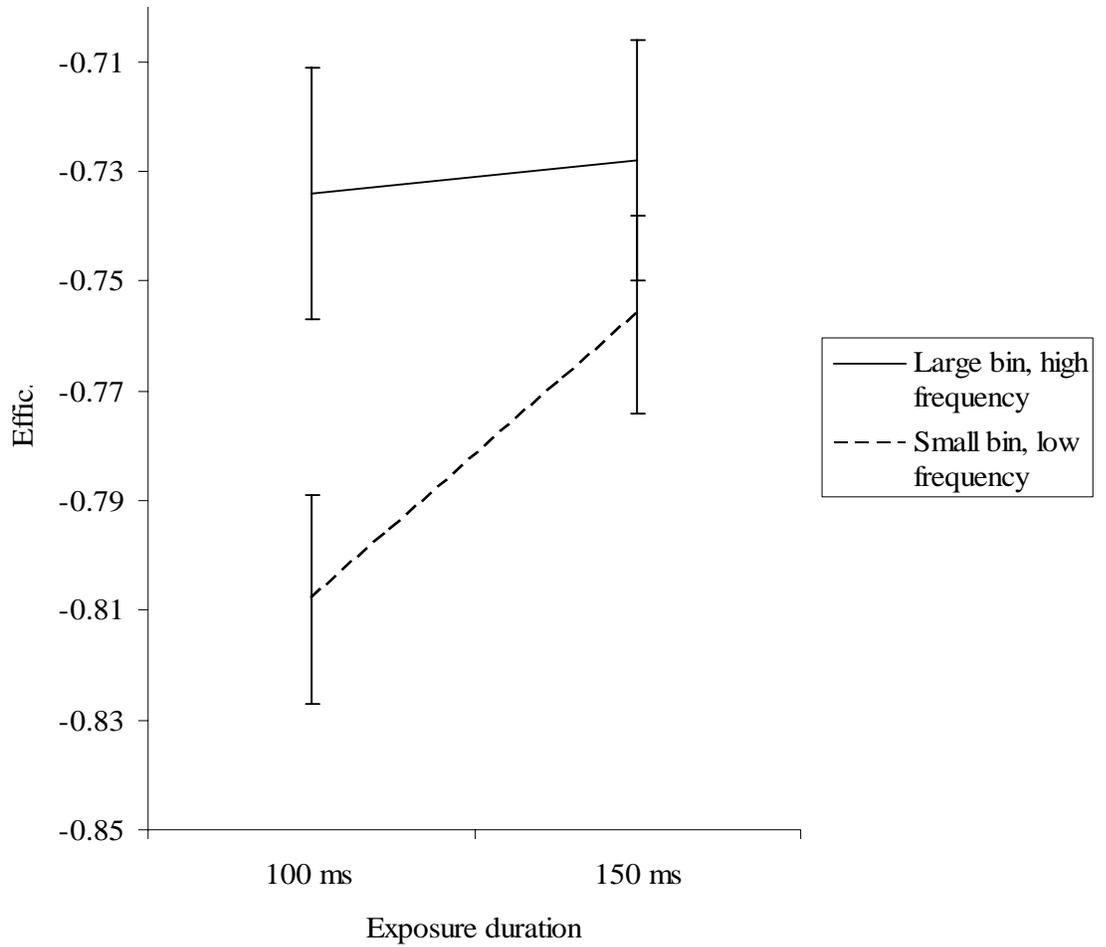


Figure 17. Log transform efficiency means for female participants in block 1 showing a significantly larger decrement in performance under small bin, low frequency conditions than under large bin, high frequency conditions when exposure duration was reduced from 150 ms to 100 ms. Effic. = Transformed efficiency scores.

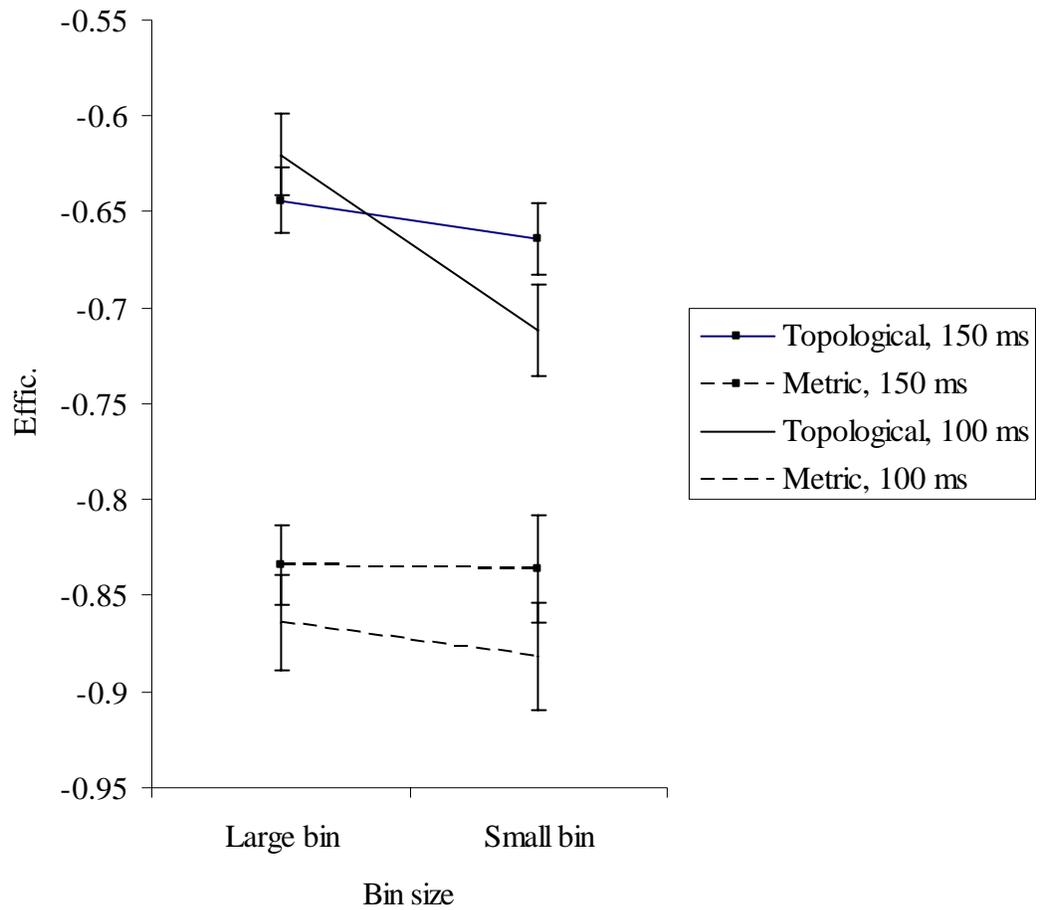


Figure 18. Log transform efficiency means for female participants in block 1 showing a proportionally greater decrement under small bin compared to large bin conditions for the topological task when exposure duration was reduced. Effic. = Transformed efficiency scores.

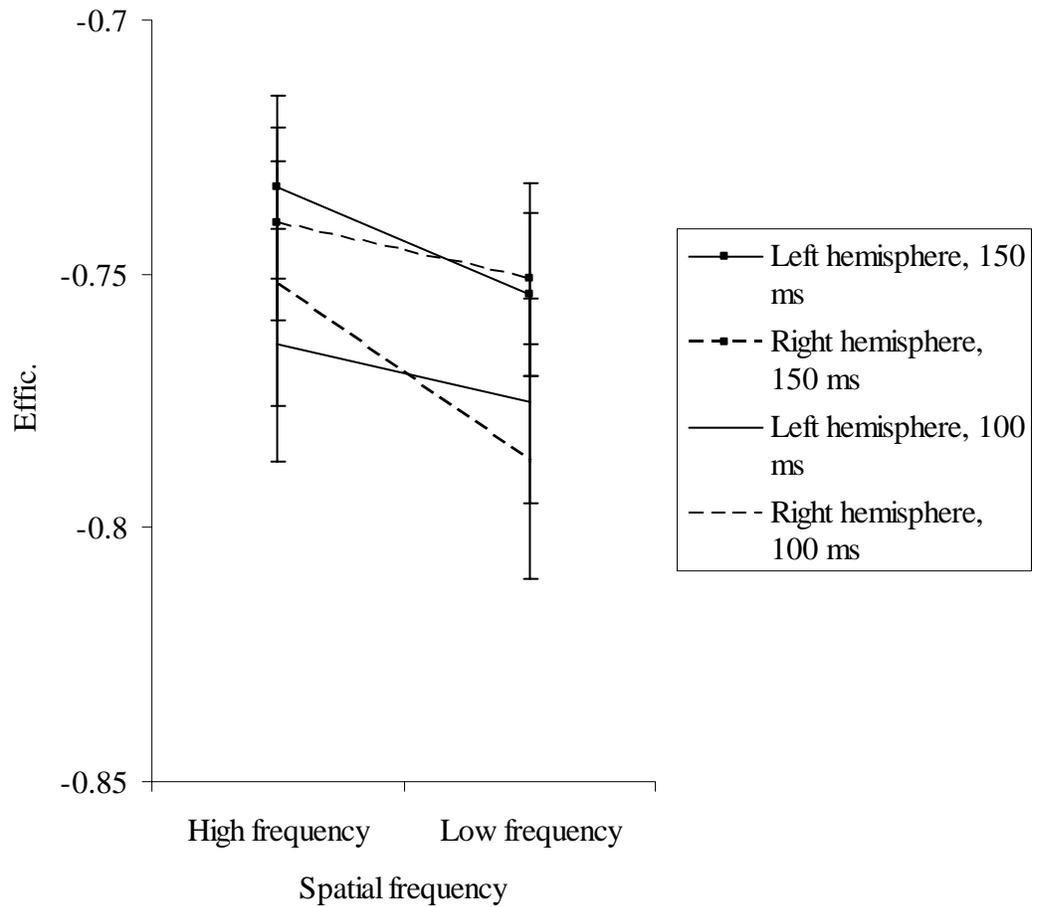


Figure 19 Log transform efficiency means for female participants in block 1 showing a reversal of the left hemisphere advantage under high frequency at 150 ms to a right hemisphere advantage under high frequency at 100 ms and a reversal of the left hemisphere disadvantage under low frequency at 150 ms to a right hemisphere disadvantage under low frequency at 100 ms. Effic. = Transformed efficiency scores.

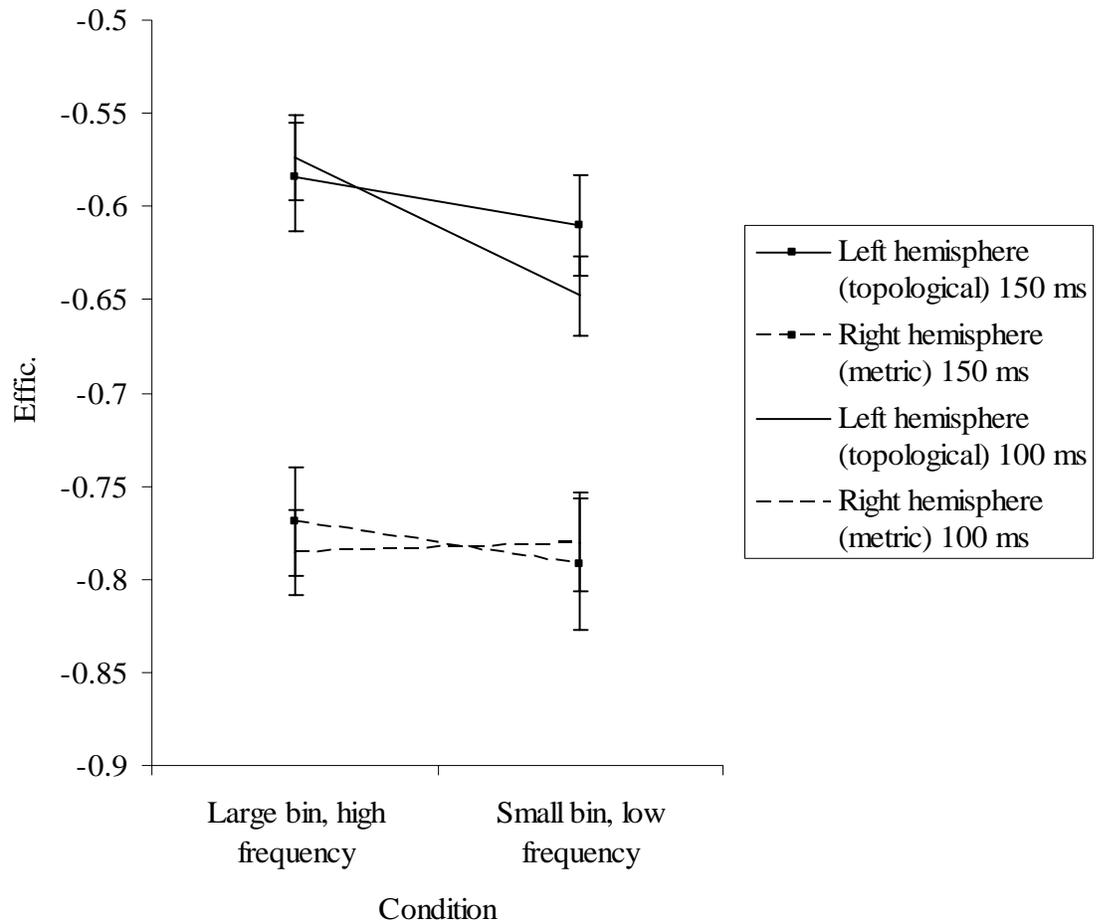


Figure 20. Log transform efficiency means for male participants in block 2 showing an increased decrement in efficiency under small bin, low frequency for the left hemisphere (topological task) and an increase in efficiency under small bin, low frequency conditions for the right hemisphere (metric task) at 100 ms exposure duration. Effic. = Transformed efficiency scores.

However, no significant five-way interaction (task x hemisphere x bin x frequency within and exposure duration between) was found. The only exposure duration effect found was mediated by a task x bin interaction,  $F(1, 22) = 8.197, p = .010$ , showing an increased advantage for large bin conditions for the topological task and a reversal of the decrement in performance of the metric task under small bin conditions (Appendix Wiii).

Exposure duration did not affect the single task x hemisphere interaction found under small bin, high frequency conditions,  $F(1, 21) = 5.210, p = .033$ . This interaction showed a left hemisphere advantage for the topological task and a right hemisphere advantage for the metric task as would be predicted by two-process theory. No other task x hemisphere interactions or exposure duration x task x hemisphere interactions were found. However, variation in exposure duration did elicit an interaction with hemisphere (task consistent) x condition (hemispherically consistent) interaction,  $F(1, 21) = 5.055, p = .035$ . This interaction showed that the right hemisphere (metric task) performed better under large bin, low frequency conditions than small bin, high frequency conditions at 150 ms but better under small bin, high frequency conditions than large bin, low frequency conditions at 100 ms. On the other hand, the left hemisphere (topological task) performed better under small bin, high frequency conditions than large bin, low frequency conditions at 150 ms but better under large bin, low frequency conditions than small bin, high frequency conditions at 100 ms as shown in Figure 21.

#### Female Participants

Exposure duration had a significant effect on the test of the a priori hypotheses,  $F(1, 28) = 6.28, p = .018$ , showing an improved performance by the left hemisphere

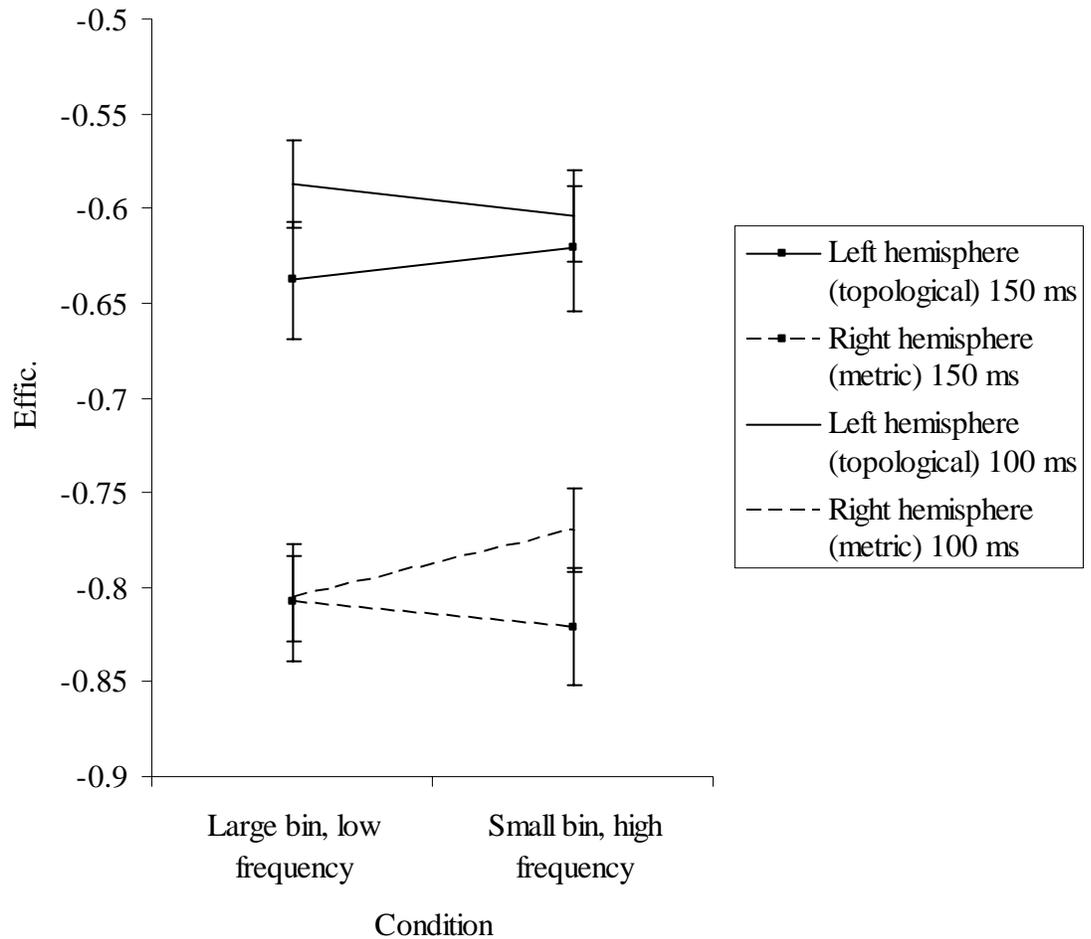


Figure 21. Log transform efficiency means for male participants in block 2 showing that at 150 ms exposure duration, the right hemisphere was more efficient under large bin, low frequency conditions and the left hemisphere was more efficient under small bin, high frequency conditions but at 100 ms exposure duration, the right hemisphere was more efficient under small bin, high frequency conditions and the left hemisphere was more efficient under large bin, low frequency conditions. Effic. = Transformed efficiency scores.



(topological task) under large bin, high frequency conditions ( $M = -.587$ ,  $SE = 0.019$  at 150 ms and  $M = -.571$ ,  $SE = 0.024$  at 100 ms) and decreased performance by the left hemisphere (topological task) under small bin, low frequency conditions when exposure duration was reduced ( $M = -.650$ ,  $SE = 0.030$  at 150 ms and  $M = -.697$ ,  $SE = 0.037$  at 100 ms). Performance for the right hemisphere (metric task) deteriorated when exposure duration was reduced for both the large bin, high frequency condition ( $M = -.763$ ,  $SE = 0.019$  at 150 ms and  $M = -.784$ ,  $SE = 0.023$  at 100 ms) and small bin, low frequency condition ( $M = -.803$ ,  $SE = 0.023$  at 150 ms and  $M = -.819$ ,  $SE = 0.029$  at 100 ms; Figure 22).

Exposure duration had no effect on a four-way interaction between task, hemisphere, bin and frequency,  $F(1, 28) = 8.375$ ,  $p = .008$ , but did interact with task, hemisphere and bin,  $F(1, 28) = 4.880$ ,  $p = .036$ . This interaction showed that the differences between the hemispheres in the efficiency with which they performed each task under large and small bin conditions disappeared when exposure duration was reduced (Appendix Xiii and Xiv).

Exposure duration did not affect task x hemisphere interactions found under three of four conditions. Significant task x hemisphere interactions were noted under large bin, high frequency,  $F(1, 28) = 5.340$ ,  $p = .028$ , large bin, low frequency,  $F(1, 28) = 6.540$ ,  $p = .016$ , and small bin, high frequency,  $F(1, 27) = 6.392$ ,  $p = .018$ . In each case, the topological task was performed more efficiently with the left hemisphere and the metric task was performed more efficiently with the right. The test of inconsistency rendered no significant hemisphere (task consistent) x condition (hemispherically inconsistent) interaction and no interaction with exposure duration (Appendix X).

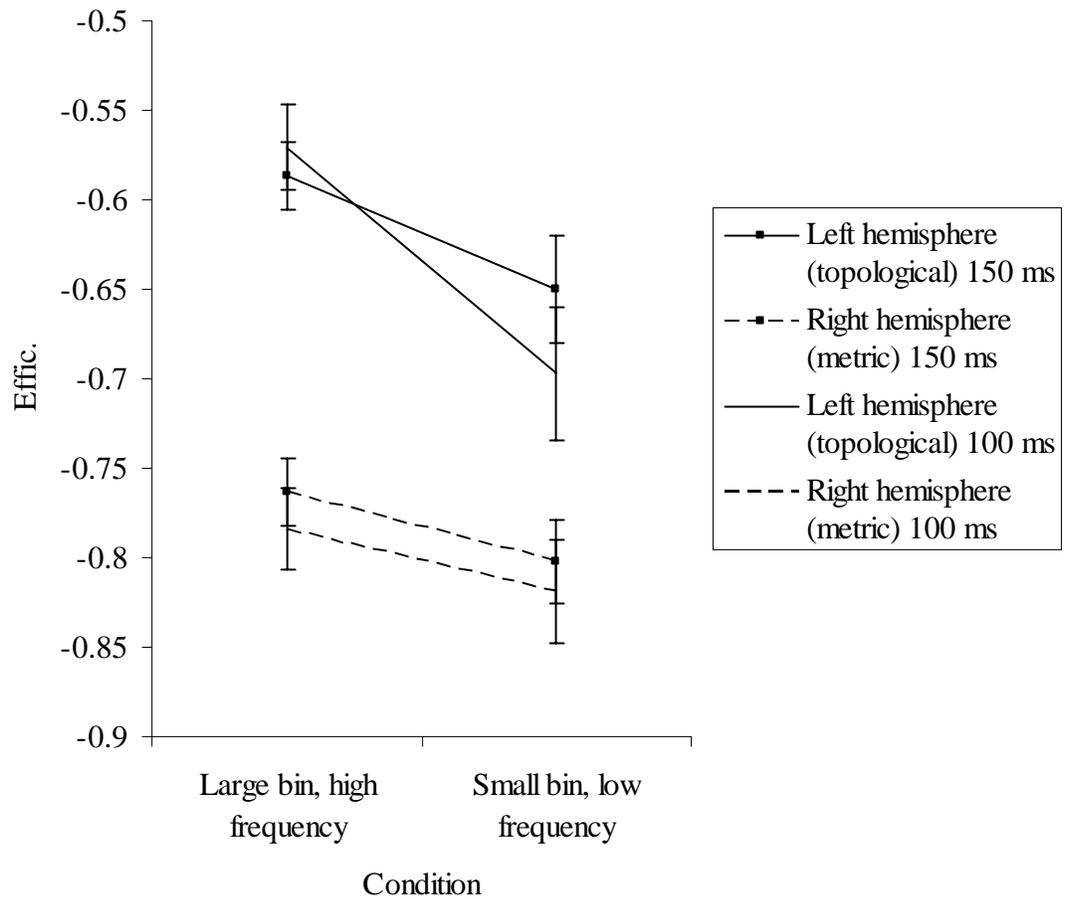


Figure 22. Log transformed efficiency scores for female participants in block 2 showing an interaction between exposure duration, hemisphere (task consistent) and condition (hemispherically inconsistent). Both hemispheres (task consistent) performed more poorly under small bin, low frequency conditions, but the drop in performance between large bin, high frequency and small bin, low frequency was larger for the left hemisphere (topological task) than the right hemisphere (metric task). Effic. = Transformed efficiency scores.

### *Within Subjects*

The data for the 100 ms exposure duration group were analyzed separately in order to test the double double dissociation. In a 5 within (block, task, hemisphere, bin and frequency) and one between (sex) ANOVA, a significant interaction was found between block, task, bin and sex,  $F(1, 16) = 4.747, p = .045$ . Paired t-tests with corrected alpha set to .002 (Bonferroni) showed that while not all mean comparisons reached significance, higher efficiency scores were noted without exception on block 2 for each pair for both male and female participants (Appendix Y). For all subsequent analyses, the blocks were examined separately for male and female participants.

#### *Block 1.*

##### Male Participants

No significant hemisphere (task consistent) x condition (hemispherically inconsistent) interaction was found nor was a four-way interaction found. A significant task x bin interaction was noted,  $F(1,11) = 5.288, p = .042$ , showing a relatively larger advantage for the topological task under large bin conditions than small compared to the advantage seen for the metric task under large bin over small. No significant task x hemisphere interactions were found for any conditions, but a significant hemisphere (task consistent) x condition (hemispherically consistent) interaction was found,  $F(1, 14) = 7.569, p = .016$  showing better efficiency for the left hemisphere (topological task) under large bin, low frequency conditions [Appendix Z]. However, this interaction cannot be interpreted without task x hemisphere consistency.

## Female Participants

A significant hemisphere (task consistent) x condition (hemispherically inconsistent) interaction was found,  $F(1, 11) = 7.469, p = .019$ , showing proportionally greater efficiency for the left hemisphere (topological task) under large bin, high frequency conditions ( $M = -.614, SE = 0.031$ ) than small bin, low frequency conditions ( $M = -.722, SE = 0.035$ ) compared to the right hemisphere (metric task) under large bin, high frequency conditions ( $M = -.854, SE = 0.036$ ) and small bin, low frequency conditions ( $M = -.895, SE = 0.039$ ). Figure 23 depicts this interaction.

However, no significant four-way interaction was found. A significant task x bin interaction was found,  $F(1, 11) = 16.910, p = .001$ , showing a relatively greater advantage for large bin over small bin conditions for the topological task compared to the advantage of large bin over small bin conditions for the metric task. As well, a marginally significant hemisphere x frequency interaction was noted,  $F(1,11) = 4.256, p = .064$  showing a relatively greater right hemisphere advantage for high spatial frequency over low spatial frequency than the left hemisphere advantage for high spatial frequency over low spatial frequency.

No task x hemisphere interactions reached significance but a significant hemisphere (task consistent) x condition (hemispherically consistent) interaction emerged,  $F(1, 13) = 12.490, p = .004$ , showing better performance of the right hemisphere under small bin, high frequency conditions and better performance of the left hemisphere under large bin, low frequency conditions. However, without confirmation of task x hemisphere consistency, this interaction is not interpretable (Appendix AA).

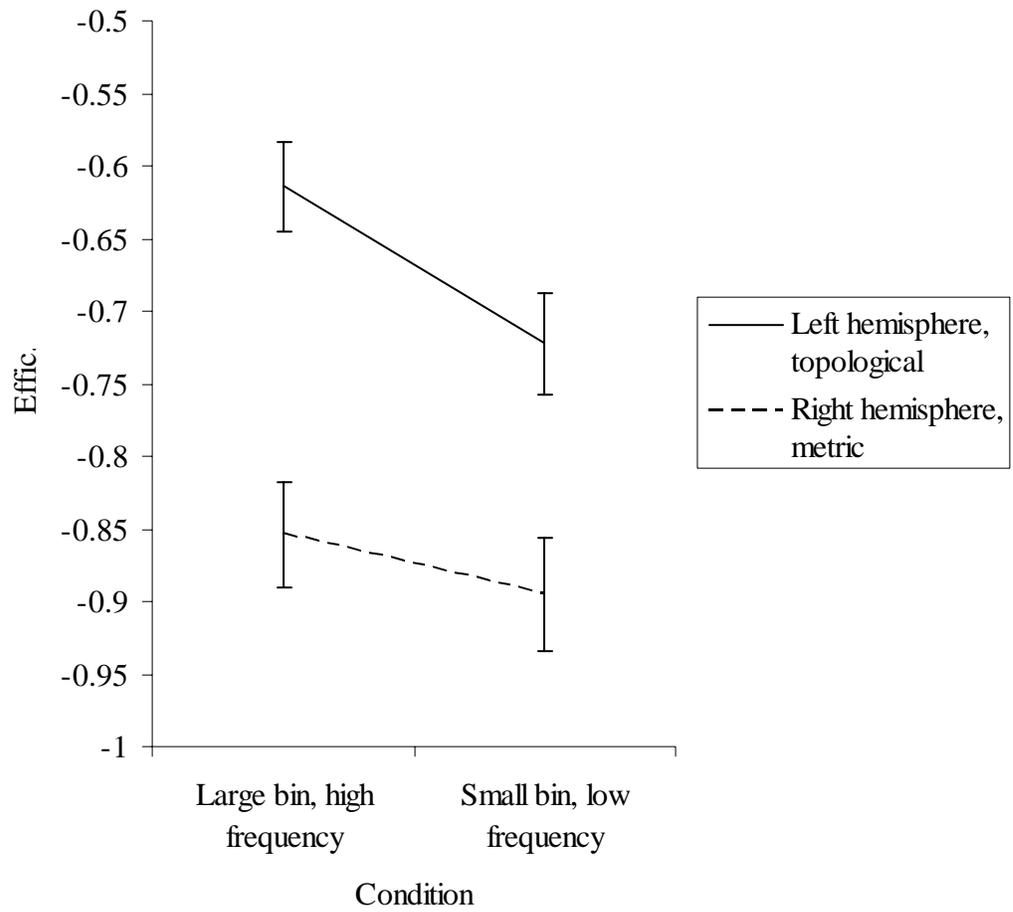


Figure 23. Log transform efficiency means for female participants in block 1 showing an interaction between hemisphere (task consistent) and condition (hemispherically inconsistent). Performance was generally better under large bin, high frequency conditions but proportionally better for the left hemisphere (topological task). Effic. = Transformed efficiency scores

## *Block 2.*

### Male Participants

A significant hemisphere (task consistent) x condition (hemispherically inconsistent) interaction was found,  $F(1, 14) = 9.536, p = .008$ , showing better performance of the left hemisphere (topological task) under large bin, high frequency conditions ( $M = -.574, SE = 0.023$ ) than small bin, low frequency ( $M = -0.648, SE = 0.022$ ) and marginally better performance of the right hemisphere (metric task) under small bin, low frequency conditions ( $M = -0.780, SE = 0.030$ ) than large bin, high frequency ( $M = -.786, SE = 0.024$ ) as shown in Figure 20. However, no significant four-way interaction was found. A significant three-way interaction was noted between task, bin and frequency,  $F(1, 12) = 4.570, p = .054$ . For the topological task, performance was more efficient under high frequency conditions for both large bin and small bin conditions (Appendix BBiii). For the metric task, performance was more efficient under high frequency conditions for large bin but for small bin conditions, no meaningful difference was found between low frequency conditions and high frequency conditions (Appendix BBiv). As well a significant three-way interaction was found between task, hemisphere and bin,  $F(1, 11) = 5.107, p = .043$ . Under large bin conditions, both tasks were performed better by the left hemisphere than the right. Under small bin conditions, the predicted task x hemisphere interaction emerged with better performance of the topological task by the left hemisphere over the right and better performance of the metric task by the right hemisphere over the left (Figures 24 and 25).

A single significant task x hemisphere interaction was found under small bin, high frequency conditions,  $F(1, 14) = 10.899, p = .005$ . This interaction showed

a

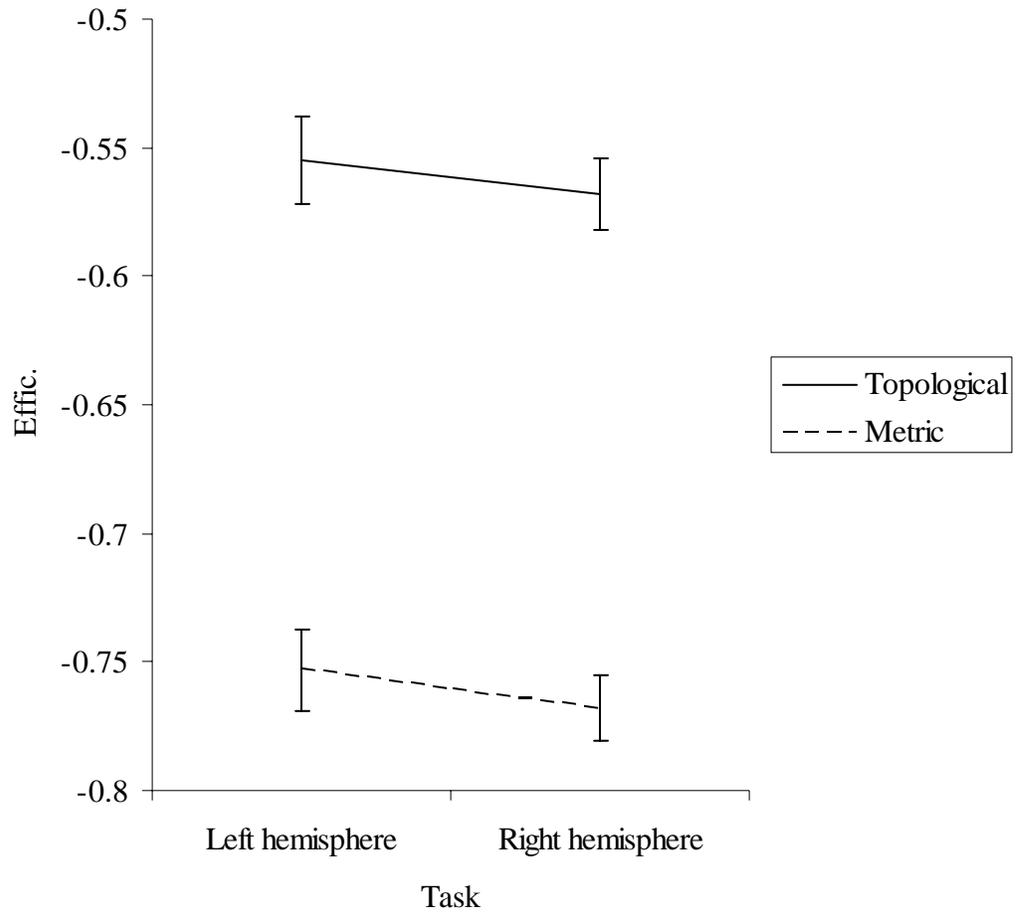


Figure 24. Log transformed efficiency scores for male participants in block 2 showing better left hemisphere performance of both tasks under large bin conditions. Effic. = Transformed efficiency scores.

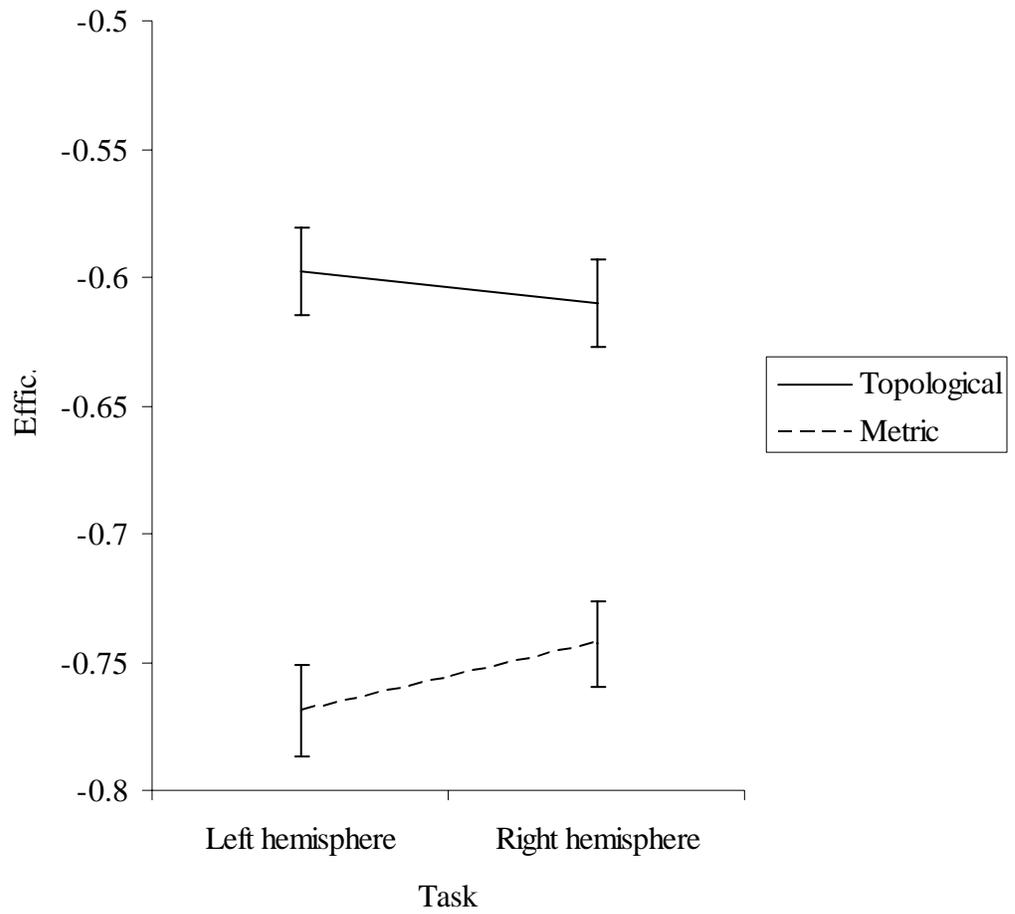


Figure 25. Log transformed efficiency scores for male participants in block 2 showing better left than right hemisphere performance of the topological task and better right than left hemisphere performance of the metric task under small bin conditions. Effic. = Transformed efficiency scores.

left hemisphere advantage for the topological task and a right hemisphere advantage for the metric task as shown in Figure 26. In addition, the test of inconsistency rendered a marginally significant hemisphere (task consistent) x condition (hemispherically consistent) interaction,  $F(1, 14) = 4.393, p = .06$ , showing greater efficiency for the right hemisphere (metric task) under small bin, high frequency conditions than large bin, low frequency conditions and greater efficiency for the left hemisphere (topological task) under large bin, low frequency conditions than small bin, high frequency conditions, but because task x hemisphere consistency could not be confirmed this interaction was not interpretable (Appendix BB).

#### Female Participants

A significant hemisphere (task consistent) x condition (hemispherically inconsistent) interaction was found,  $F(1, 11) = 13.732, p = .003$ , showing a relatively greater efficiency advantage for the left hemisphere (topological task) under large bin, high frequency conditions ( $M = -.571, SE = 0.027$ ) than small bin, low frequency conditions ( $M = -.697, SE = 0.049$ ) compared to the right hemisphere (metric task) under large bin, high frequency conditions ( $M = -.784, SE = 0.028$ ) and small bin, low frequency conditions ( $M = -.819, SE = 0.037$ ) as seen in Figure 22. No significant four-way interaction was found. Only main effects for task,  $F(1, 9) = 101.925, p < .001$ , bin,  $F(1, 9) = 9.387, p = .013$ , and frequency,  $F(1, 9) = 8.155, p = .019$ , were found showing better performance on the topological task than the metric task, under large bin conditions than small bin conditions and under high frequency conditions than low frequency conditions respectively. No task x hemisphere interactions were found under

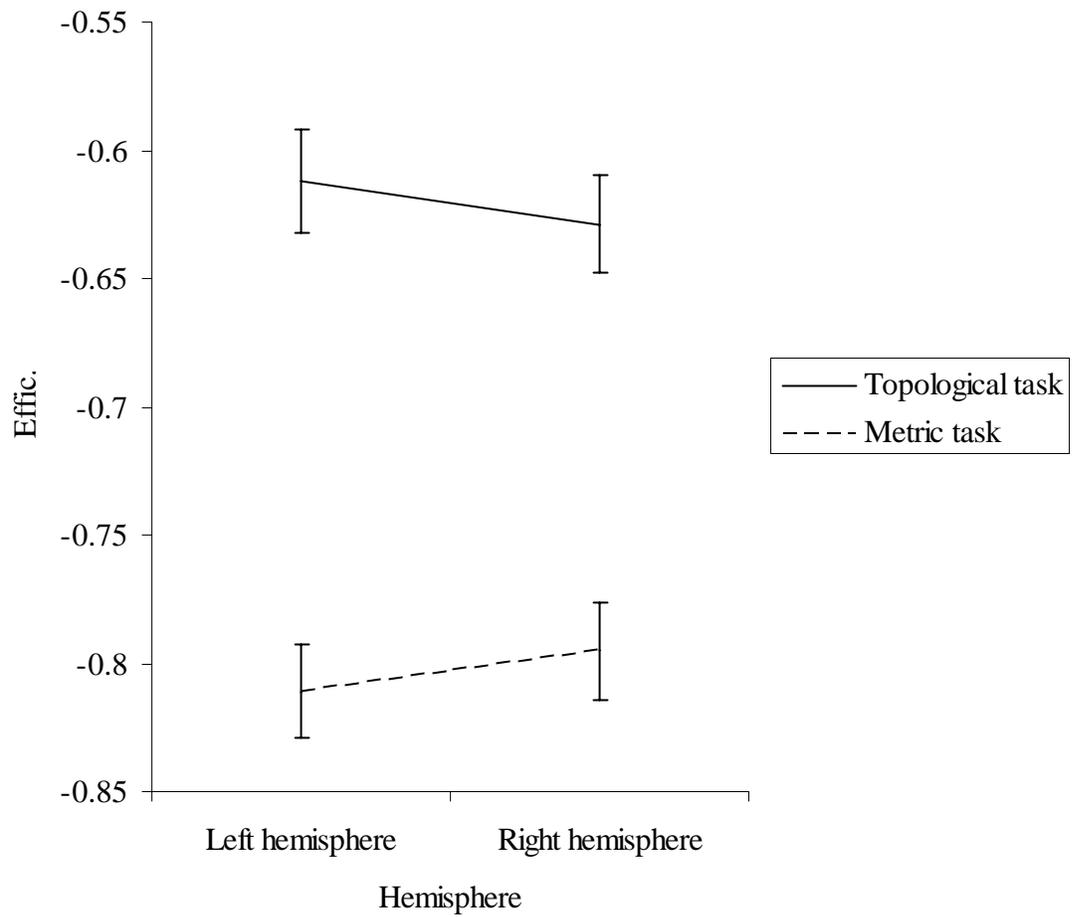


Figure 26. Log transformed efficiency scores for male participants in block 2 showing a task x hemisphere interaction under small bin, high frequency conditions. The topological task was performed better by the left hemisphere than the right, and the metric task was performed better by the right hemisphere than the left. Effic. = Transformed efficiency scores.

any conditions nor was a hemisphere (task consistent) x condition (hemispherically consistent) interaction noted (Appendix CC).

### Discussion

The purpose of this experiment was to test the double double dissociation under conditions that ensured unilateral presentation of the stimuli. It was expected that unilateral viewing conditions would elicit hemisphere effects for male participants and facilitate compliance with the test of inconsistency for female participants. Although no between group hemisphere effects were noted for male participants, the within analysis of the 100 ms exposure duration group rendered a hemisphere effect in the form of a task by hemisphere interaction under small bin, high frequency conditions and a task x hemisphere x bin interaction showing a relatively greater advantage for the left hemisphere on the topological task when bin size was large and a right hemisphere advantage on the metric task when bin size was small. For female participants, reducing exposure duration had a significant influence on the direction of the test of inconsistency but limitations on interpretation were imposed because task x hemisphere consistency could not be confirmed. For ease of presentation the between groups analysis will be discussed first before proceeding to the within groups analysis.

#### *Between Groups Analysis*

For male participants, reducing exposure duration was expected to elicit hemisphere effects. However, no hemisphere effects could be confirmed between the 150 ms and 100 ms exposure duration groups. In the second block, reducing exposure duration augmented the topological task advantage under large bin conditions and decreased performance of this task under small bin conditions while increasing

efficiency for the metric task under small bin conditions. Given this, the improved left hemisphere (topological task) performance under large bin, high frequency conditions and decreased performance under small bin, low frequency conditions when exposure duration was reduced can be attributed to ease of task performance not to hemisphere effects. Similarly, the increased left hemisphere (topological task) performance under large bin, low frequency conditions at 100 ms exposure duration is also likely due to ease of topological task performance at 100 ms exposure duration. Consistent with this, the right hemisphere (metric task) increase in efficiency under small bin, low frequency and small bin, high frequency conditions is likely attributable to increased ease of performance of the metric task under small bin conditions when exposure duration is reduced.

For female participants in the first block of trials, reducing exposure duration elicited a number of effects. Like their male counterparts, the topological task was easier to perform under large bin conditions and harder to perform under small bin conditions when exposure duration was reduced. Unlike their male counterparts, no advantage for the metric task under small bin conditions was found with reduced exposure duration. Rather a general decrease in performance was noted for distance judgments across both bin sizes when exposure duration was reduced. As well, reducing exposure duration had significant effects on how the hemispheres processed spatial frequency. While the left hemisphere had the performance advantage for high spatial frequencies and disadvantage for low spatial frequencies at 150 ms, the right hemisphere had the performance advantage for high spatial frequencies and disadvantage for low at 100 ms. Given these findings, the improved performance of the left hemisphere (topological

task) under large bin, low frequency conditions and of the right hemisphere (metric task) under small bin, high frequency conditions can only be attributed to greater ease of making topological judgments when bin size is large and greater processing efficiency of the right hemisphere under high frequency conditions.

In the second block, reducing exposure duration had a very counterintuitive effect. At 150 ms, when participants could process the stimuli bilaterally, the consistent task x hemisphere combinations showed advantages under large bin conditions compared to inconsistent task x hemisphere combinations, but when exposure duration was reduced, hemisphere differences were lost. To find hemisphere effects under conditions where bilateral viewing is possible, and then lose the hemisphere effects under conditions where unilateral viewing was ensured presents somewhat of an interpretation conundrum. Experiment 2 demonstrated that participants were able to saccade to the stimulus within 150 ms and thereby process the stimulus with the bilaterally projecting foveal aspect of the retina. Bilateral processing could potentially deploy asymmetrically distributed attentional processes, so that the hemisphere effects are attentional asymmetries rather than asymmetries in spatial processing. When exposure duration is reduced, attentional effects are eliminated, so hemisphere effects or a lack thereof can be attributed to asymmetry, or symmetry as the case might be, in processing the tasks.

Artifactual asymmetries can also arise in the context of task difficulty. Lavidor and Ellis, (2003) showed that less effortful tasks can be performed intra-hemispherically by the contralateral hemisphere even when stimuli were viewed foveally. More difficult tasks that require interhemispheric cooperation in order to be successfully completed

must be viewed foveally to facilitate bilateral processing as well. In this case, the tasks were less effortful under large bin conditions when exposure duration was 150 ms, so the tasks could be viewed bilaterally, but processed unilaterally so hemisphere effects would emerge under large bin conditions with exposure duration of 150 ms. When exposure duration was reduced, however, processing the stimuli under large bin conditions was more effortful and possibly required interhemispheric cooperation which was denied because the stimuli were presented unilaterally. In effect, the task was too difficult to be performed by one hemisphere alone so hemispheric asymmetries will not manifest.

#### *Within Subjects Analysis*

No significant four-way interactions were found for either male or female participants in either the first or second block so interpretation is necessarily limited. In the first block, for male participants only the test of the assumption of inconsistency was significant but this was not attributed to any hemisphere effect but rather to increased efficiency of the topological task under large bin conditions.

Male participants in the second block of trials demonstrated a facilitation of the left hemisphere advantage for the topological task when stimuli were presented under large bin conditions. The topological task advantage under large bin conditions was further augmented by high spatial frequency presentation. A right hemisphere advantage was noted for small bin conditions but frequency did not appear to have a meaningful impact on performance of the metric task. This finding suggests that the right hemisphere advantage for the metric task noted under small bin, high frequency as well as under small bin, low frequency conditions in the test of the a priori hypotheses is

likely attributable to small bin conditions rather than high frequency. The left hemisphere (topological task) advantage noted under the a priori hypotheses is likely attributable to both a left hemisphere and a topological task advantage under large bin and high frequency conditions.

For female participants in both blocks, better efficiency was noted for both the left hemisphere (topological task) and the right hemisphere (metric task) under large bin, high frequency conditions but proportionally greater efficiency was noted for the left hemisphere (topological task). In the first block, this is attributed only to main effects of task, bin and frequency as well as a topological task facilitation under large bin conditions. For the second block of trials the significant interaction in the test of the a priori hypotheses can only be attributed to better efficiency for the topological task, for large bin conditions and for high frequency stimuli.

It was reasoned that four-way interactions had not emerged in Experiment 1 for male participants because the exposure duration of the stimulus did not support unilateral presentation. Although effects of exposure duration were evident, particularly in the efficiency with which the tasks were performed and bin sizes were processed, unilateral processing did not elicit the four-way interactions between task, hemisphere, bin and frequency that were required in order to interpret the double double dissociation. In fact, reducing exposure duration did not elicit any interpretable hemisphere effects for male participants at all although when analyzed separately, the male participants in the reduced exposure duration group showed a task x hemisphere effect that was not evident in Experiment 1.

Reducing exposure duration and thereby ensuring unilateral viewing, was also expected to facilitate the emergence of hemisphere (task consistent) x condition (hemispherically consistent) interactions for female participants. Contrary to expectations, however, reducing exposure duration caused a loss of hemisphere effects under large bin, low frequency and small bin, high frequency conditions.

## GENERAL DISCUSSION

The intention of this research was to determine whether metric and topological spatial judgments were governed by the spatial frequency of the stimulus or the size of the processing attentional field. A double double dissociation was devised in order to test the asymmetrical predictions of both bin theory and spatial frequency theory using asymmetrically distributed tasks. The results of these studies suggest that bin size and spatial frequency cannot be dissociated from one another for two reasons. First, task and hemisphere consistency could not be confirmed under large bin, high frequency and small bin, low frequency conditions, the conditions under which bin theory and spatial frequency theory could be dissociated. Second, the results of these studies indicate that the asymmetrical predictions of bin theory, spatial frequency theory or both could not be confirmed using topological and metric tasks.

Fundamentally, this research attempted to explore the asymmetrically distributed interface between tasks and stimulus characteristics. While much research has been devoted to exploring asymmetry in task performance and other research dedicated to examining asymmetry in input processing, this research attempted to elaborate the three-way dialogue between task, hemispheric asymmetry and input conditions, more specifically, the asymmetry between topological and metric tasks when processed under variations in attended receptive field size and spatial frequency. The double double dissociation method was developed for this purpose. In the following sections, theoretical implications of the findings elicited by the double double dissociation will be discussed first. Then, the utility of the double double dissociation itself will be discussed.

## Comments on Theoretical Findings

The double double dissociation was predicated on task x hemisphere consistency and bin size x spatial frequency inconsistency. Each premise was tested within the four-way analysis to determine if these assumptions were met. The results indicated that neither assumption could be consistently met. Findings relating to each assumption will be discussed in turn before examining other effects.

### *The Assumption of Consistency*

The test of the assumption of consistency between task and hemisphere required a task x hemisphere interaction in the predicted direction under all combinations of bin and frequency. While typically, this interaction shows a marginal left hemisphere advantage for the topological task and a clear right hemisphere advantage for the metric task (Cowin & Hellige, 1994; Hellige & Michimata, 1989; Kosslyn et al., 1989; Rybash & Hoyer, 1992) at least one other has reported a marginal right hemisphere advantage for the metric task and a clear left hemisphere advantage for the topological task (Banich & Federmeier, 1999). Regardless, the test of the assumption of consistency predicted a left hemisphere advantage for the topological task and a right hemisphere advantage for the metric task.

The test of the assumption of consistency was not met for either male or female participants regardless of unilateral presentation or practice. For male participants, no task x hemisphere interactions were found at all when exposure duration was 150 ms. The absence of any hemisphere effects for male participants at 150 ms suggested strongly that 150 ms was sufficient time to saccade to the stimulus and this was confirmed using eye tracking in Experiment 2. A single task x hemisphere interaction

did emerge when unilateral viewing was ensured in the second block of trials under small bin, high frequency conditions. In other words, the effect only emerged when stimulus characteristics simulated those of Kosslyn et al. (1989). This interaction was mediated by a higher order interaction with bin size showing that the right hemisphere advantage for the metric task reported by Kosslyn et al. (1989) can be attributed to a right hemisphere advantage for processing input through small attentional bins, a finding that lies in opposition to the theoretically predicted right hemisphere advantage for large bin processing.

The assumption of consistency was not met for female participants either regardless of exposure duration or practice. However, unlike their male counterparts, task x hemisphere interactions were found at 150 ms exposure duration under large bin, low frequency and small bin, high frequency conditions. Hemisphere effects emerging for female participants and not male participants suggests a number of possibilities. One possibility is that female participants were not able to saccade to the stimulus within 150 ms. This is not consistent, though, with the findings of Experiment 2 that clearly showed that all participants could saccade to the stimulus within 150 ms. Another possibility is that female participants were more compliant with instructions to fixate on the centre of the screen but again the results of Experiment 2 clearly showed that all participants shift the direction of their gaze at stimulus onset. A final possibility is that the hemisphere effects noted for female participants at 150 ms are artifactual. This last possibility deserves further consideration.

It is an assumption that hemispheric asymmetry in reaction time is due to differential processing capabilities of the hemispheres and that all other factors

contributing to the response such as time to saccade, inspect, and process stimulus characteristics and prepare a response are held constant across the hemispheres. However, artifactual hemisphere effects can arise when experimental conditions are such that these other factors are asymmetrically performed. For example, if simply by virtue of the musculature of the eye, participants are able to move more rapidly to a target in the left visual field, an artifactual right hemisphere advantage will result. Similarly, if a participant can foveate more quickly to the right visual field, an artifactual left hemisphere advantage will result.

In the context of the present results, artifactual hemispheric results are not likely due to a central fixation bias although this has been previously reported to impact hemispheric asymmetries (Batt, Underwood & Bryden, 1995, Jordan, Patching & Milner, 1998). In Experiment 2, participants were found to fixate to the left of centre. With a general left of center fixation, participants could be expected to saccade to the left visual field faster than the right leading to an artifactual right hemisphere advantage. However, the results of Experiment 2 showed no further leftward movement in 150 ms than rightward. In other words, the results were not consistent with a left of centre bias. Rather, it is more likely that the left of centre bias seen in Experiment 2 was attributable to a systematic calibration issue. Furthermore, reducing exposure duration which precluded saccadic movement to the stimulus had no effect on hemisphere advantages for their respective tasks. This suggests that asymmetry in spatial judgments was unaffected by bilateral processing. This is consistent with previous findings showing asymmetrical spatial judgments with exposure durations of 150 ms (Hellige & Michimata; Kosslyn et al., 1989c; Kosslyn et al., 1989c; Niebauer & Christman, 1998).

Alternatively, artifactual hemisphere effects might be attributed to task difficulty. Jordan et al. (1998) described unilateral processing for easy tasks and bilateral processing for more effortful tasks regardless of foveal viewing. It is possible that despite bilateral viewing of the stimulus, female participants still processed the stimuli unilaterally because at 150 ms exposure duration, the tasks were easy. At 100 ms exposure duration, however, the tasks were more effortful and required bilateral processing. Bilateral processing was prohibited because the stimulus could not be foveally processed at 100 ms, so hemisphere effects did not emerge. For male participants, 150 ms duration might have been so long that participants were not only able to view the stimulus bilaterally, but process it bilaterally as well which would account for the lack of hemisphere effects at 150 ms and the presence of hemisphere effects at 100 ms. Essentially, what is being suggested is a function that describes a relationship between task difficulty, exposure time and hemispheric processing. An easy task will be unilaterally processed regardless of exposure duration so hemisphere effects will emerge. A hard task requiring bilateral processing will need longer exposure duration before it can be completed. Task difficulty would likely vary according to demographic variables such as age and sex and prior training.

When unilateral viewing was guaranteed, task x hemisphere consistency was only found for male participants under small bin, high frequency conditions, in other words, under conditions that replicate those of others (Hellige & Michimata, 1989; Kosslyn et al., 1989). The interaction was consistent with two-process theory. Unlike previous work, though, the double double dissociation allowed for the examination of the effect of different input conditions on the interaction and in this regard the double

double dissociation did not disappoint. The task x hemisphere interaction emerged within the context of higher-order interactions involving task and input conditions showing that input conditions impacted the performance of the tasks differently. The higher order interactions showed that the task x hemisphere interaction was influenced by bin size with a right hemisphere advantage for the metric task emerging when the stimulus was small and a left hemisphere advantage for the topological task being facilitated by large stimuli. These findings suggest that the right hemisphere advantage for the metric task might be attributed to a right hemisphere advantage for small bin conditions while the marginal left hemisphere advantage for the topological task might be compromised by small bin presentation. In other words, the task x hemisphere interaction for male participants is attributable not solely to hemispheric asymmetry for spatial subsystems but rather to hemispheric asymmetry for particular task and attentional bin size combination.

Task x hemisphere consistency was not confirmed for either large bin, high frequency or for small bin, low frequency in any analysis which proved problematic for interpreting the test of the a priori hypotheses. A strict interpretation of this finding would be that the tasks were not asymmetrically processed under these conditions. However, considering that task complexity can impact the emergence of asymmetry, the lack of asymmetry here might well reflect ceiling and floor effects. Main effects for bin size and frequency all showed better performance under large bin and high frequency conditions and poorer performance under small bin and low spatial frequency. The combination of large bin and high frequency might have made the task so easy that either hemisphere could perform either task. The combination of small bin and low

frequency represented the most difficult combination of input conditions, so regardless of hemispheric specialization, perhaps neither hemisphere reached more than minimal efficiency on either task.

#### *Assumption of Inconsistency*

The assumption of inconsistency required hemispheric inconsistency between input conditions being tested in the double double dissociation. This was examined by testing for asymmetric processing of input conditions that were theoretically predicted to be consistent. In this case, the left hemisphere should have outperformed the right hemisphere under small bin, high frequency conditions because both bin theory and spatial frequency theory predicted a left hemisphere advantage under these conditions. Similarly, the right hemisphere should have outperformed the left under large bin, low frequency conditions because both theories predicted a right hemisphere advantage under large bin, low frequency. However, the test depends upon meeting the assumption of consistency between task and hemisphere. Otherwise, an interaction might be due to asymmetrical performance of the tasks rather than the consistent combination of input characteristics.

The test of inconsistency could only be examined for female participants in the second block of trials when exposure duration was 150 ms because it was under these conditions that task x hemisphere consistency could be confirmed. Hemispheric consistency between small bin and high frequency could not be confirmed for the left hemisphere, nor could consistency between large bin and low frequency be confirmed for the right hemisphere. In other words, the assumption of inconsistency was violated.

However, given that participants were able to saccade to the stimulus and therefore process the stimulus bilaterally, this violation was not surprising.

Reducing exposure duration had a significant effect on the tests of the assumption of inconsistency for male participants in the second block of trials and female participants in the first block of trials although interpretation is limited by the lack of task x hemisphere consistency. For female participants in the first block of trials, this interaction was attributable to a relatively greater drop in performance under small bin, high frequency conditions for the left hemisphere (topological task) but task x hemisphere consistency was not confirmed under either small bin, high frequency or large bin, low frequency conditions so interpretation is duly constrained. For male participants in block 2, reducing exposure duration resulted in a reversal of the left hemisphere (topological task) advantage under small bin, high frequency found at 150 ms exposure duration to a left hemisphere (topological task) advantage for large bin, low frequency at 100 ms exposure duration. Similarly, the right hemisphere (metric task) advantage under large bin, low frequency conditions at 150 ms was reversed to create a right hemisphere (metric task) advantage for small bin, high frequency conditions at 100 ms. Although these results might seem to contradict the predictions of bin theory and spatial frequency theory, caution is warranted given that consistency between task and hemisphere could not be confirmed under large bin, low frequency conditions.

Although interpretation for the test of inconsistency for male participants in the second block was limited by a lack of task x hemisphere consistency confirmation it was curiously consistent with other tests of inconsistency. When a significant test of inconsistency was found, in each case it demonstrated better performance of the left

hemisphere (topological task) under large bin, low frequency conditions and better performance of the right hemisphere (metric task) under small bin, high frequency conditions. These findings lie in direct contradiction to the asymmetric predictions of bin theory and spatial frequency theory. In examining higher order interactions, the findings for the test of inconsistency are likely attributable to a topological task and a left hemisphere advantage under large bin conditions and a metric task and right hemisphere advantage under small bin conditions.

Generally, the topological task showed a relatively greater advantage under large bin conditions. The facilitation of topological judgments under large bin conditions contradicts Kosslyn, Chabris, Marsolek and Koenig (1992)'s contention that the topological task is performed better by activating small receptive fields. It is somewhat difficult to determine the reason for their hypothesis but presumably they anticipated that the categorization of a spatial relationship would not require the use of large receptive fields because the fine discriminations needed for distance judgments and facilitated by coarse coding were not needed in order to categorize a relationship. The data from the present studies suggests that both tasks benefit from the activation of large receptive fields, but the topological task benefited more than the metric task.

The relatively larger advantage noted for relational judgments when bin size was large might be attributable to easier relational judgments when the stimulus is large but could also be attributed to compromised distance judgments when the stimulus reference point was round. Judging distance from the periphery of a circle requires first, a determination of the precise point at which the dot and periphery line up along a hypothetical vertical axis. This is necessary because judgments from regions of the

periphery that are adjacent to this vertical axis would also be a greater distance away from the dot because of the curve in the periphery of the large circle. This additional processing component makes judging distances more difficult when the reference point is curvilinear.

Importantly, for male participants after sufficient practice, an interaction was found showing that the topological task advantage under large bin conditions was augmented by high spatial frequency presentation. Although this finding might appear to contradict the generally established notion that larger receptive fields are tuned to lower spatial frequencies and smaller receptive fields to high spatial frequencies, these results can be predicted with reference to the principle of input redundancy. Sergent and Hellige (1986) proposed that redundancy or physical overlap of receptive fields is the critical determinant in spatial frequency processing. In short, the greater the overlap in receptive fields, the higher the spatial frequency that can be extracted. If it is the case that greater overlap facilitates the extraction of higher frequencies then the critical issue is not receptive field size but degree of overlap.

The mechanism through which redundancy occurs has not been well delineated but could be consistent with hierarchical models (Rao & Ballard, 1999; McGraw, Levi, & Whitaker, 1999; Bressloff & Cowan, 2002). For example, beginning with the basic observations of Hubel and Weisel (1977), lateral geniculate neurons interface with circular symmetric neurons which synapse with simple cells arranged in small receptive fields which then synapse with complex cells arranged in medium-sized receptive fields before finally connecting to hypercomplex cells arranged in large receptive fields and which form hypercolumns in the cortical layers. Recent imaging work supports this

arrangement (Smith, Singh, Williams & Greenlee, 2001).

Feedback or back projected models provide for neural connections from higher visual cortical areas to low cortical areas. These connections have proved to be extensive in the cat and monkey visual cortex and have been shown to increase receptive field sizes dramatically and enhance response (Angelucci & Bullier, 2003; Lamme, Super & Spekreijse, 1998; Mareschal, Henrie & Shapley, 2002; Sceniak, Ringach, Hawken, & Shapely, 1999). Restructuring of receptive fields can occur rapidly within 50 ms of stimulus onset (Wortgotter, Suder, Zhao, Kerscher, Eysel & Funke, 1998). The fundamental premise of feedback models is that mismatches in response tuning occur from one level of processing to the next and when this happens, projections from the higher level to the lower level act to correct the mismatch. For example, when a small receptive field tuned to high spatial frequency is activated, the extent of back projection is great in order to reduce the spatial frequency threshold of that small cell.

Backprojections inhibit the inhibition of the smaller receptive field effectively lowering its threshold for responding and increasing its size. The higher the frequency of the stimulus, the more back propagation is needed before the spatial tuning of the cellular layers matches. With repeated feedback iterations, the area of activation increases perhaps reflecting increases in the diameter of the hypercolumn. As well, the number of redundant inputs into each successive layer of processing increases which according to Sergent and Hellige (1986) would facilitate the extraction of task relevant higher spatial frequencies. Whether hypercolumns are asymmetrically represented is not known but the present data shows asymmetrical processing for both bin size and spatial frequency suggesting the possibility of physiological asymmetries in the organization of

backprojection systems.

The facilitation of performance under large bin conditions, when spatial frequency is high might then be explained in terms of increased redundancy. A large stimulus activates a cortical receptive field composed of multiple small receptive fields. Because multiple small receptive fields are activated, the proportion of backprojection increases with the number of small receptive fields activated by the large stimulus. In other words, total redundancy in the system increases thereby facilitating the extraction of high spatial frequencies.

The advantage to the backprojected models is that they can account for the spatiotemporal characteristics of receptive fields, a characterization of receptive fields that has been the object of recent interest and investigation. In terms of the present study, the manipulations of bin size and spatial frequency might be said to be manipulations of the spatiotemporal aspects of input processing although such a statement assumes a one-to-one correspondence between input characteristics and processing characteristics. Regardless, the results of this research provide evidence for the additional influence of task demands. This raises difficult questions about the generalizability of these models across tasks. It might well be that the receptive fields of each hemisphere are so plastic that they can accommodate the performance of any task so that observed hemisphere asymmetries are truly attributable to asymmetries in task performance rather than input processing.

#### *A priori hypotheses*

The double double dissociation was designed to determine if spatial frequency or bin theory was driving the two-process effect. However, the double double dissociation

makes two assumptions; first, that the topological task is mediated by the left hemisphere and the metric task is mediated by the right hemisphere and second, that large bin and low spatial frequency are mediated by the right hemisphere and small bin and high spatial frequency are mediated by the left hemisphere. The results of these studies demonstrated that task x hemisphere consistency was not reliably found across all combinations of bin and frequency. It was most consistently found under small bin, high frequency conditions which are the same conditions under which the stimuli have been presented elsewhere (Kosslyn et al., 1989; Hellige & Michimata, 1989). This finding is consistent with others who have noted difficulties replicating the effect (Bruyer, Scailquin, & Coibion, 1997; Wilkinson & Donnelly, 1999) and speaks to the tenderness of the effect. Although consideration must be given for the lack of confirmation for task x hemisphere consistency, the results also suggest that the asymmetrical predictions of bin theory might not be accurate in light of the right hemisphere (metric task) advantage under small bin conditions and left hemisphere (topological task) advantage under large bin conditions. Furthermore, the finding that processing through large receptive fields is augmented by the presentation of stimuli at high spatial frequency challenges the assumption that cognitive processing is true to the mathematically defined relationship between large bin and low frequency and between small bin and high frequency. Because of difficulties meeting the assumptions of consistency and inconsistency, the test of the a priori hypotheses could not be interpreted beyond the effects noted in the higher order interactions.

#### *Four-way Interaction*

Given the predictions made by two-process theory between task and hemisphere,

the predictions made by bin theory and spatial frequency theory between hemisphere and bin size and hemisphere and spatial frequency respectively and the mathematically defined relationship between large bin and low frequency and between small bin and high frequency, a four-way interaction was expected. In the present data, however, the requisite four-way interactions were difficult to find. Four-way interactions emerged for female participants at 150 ms but were lost when exposure duration was reduced because of a lack of hemisphere effects. The lack of hemisphere effects for male participants seemed a likely explanation for the loss of the four-way interaction at 150 ms exposure duration. Hemisphere effects were found when exposure duration was reduced but no four-way interactions emerged because of a lack of hemisphere x frequency interaction.

The four-way interactions that emerged showed that although both hemispheres performed more poorly under small bin, low frequency conditions, the decrement in performance was largest for the right hemisphere on the metric task. Right hemisphere performance was equivalent under all other conditions suggesting that the right hemisphere can assess distances using either large bin or small but is significantly compromised when processing low spatial frequencies through small receptive fields. This is consistent with a redundancy model. At low spatial frequency, considerable temporal resolution of the stimulus is required to breach threshold for processing of the input, but with a small receptive field, redundancy is limited because of fewer backprojections so more iterations through the backprojection system are needed before the stimulus can be processed. The result is compromised performance. This compromise, however, was most notable for the right hemisphere suggesting that

contrary to spatial frequency theory, the right hemisphere is not better equipped to process low spatial frequencies.

### *Main Effects*

Consistent main effects emerged throughout these studies for task, bin size and frequency. These main effects showed better performance on the topological task compared to the metric task, better performance under large bin conditions than small and better performance under high spatial frequency conditions than low.

#### *Main Effect of Task.*

The most consistent result was a main effect for task showing greater efficiency for the topological task in all cases. The task main effect was anticipated based on previous findings. Studies using the bar and dot stimulus have consistently found faster and more accurate performance of the topological task and slower, less accurate performance of the metric task (Kosslyn et al., 1989; Hellige & Michimata, 1989; Cowin & Hellige, 1994). Participants in the present study were no different. These findings collectively suggest that categorizing a spatial relationship might simply be easier than judging the distance between two objects regardless of hemisphere of presentation as has been suggested elsewhere (Parrot, Doyon, Demonet & Cardebat, 1999).

#### *Main Effect of Bin.*

The main effect found for large bin conditions might reflect a general stimulus energy advantage making judgments easier under large bin conditions but might also be attributed to the peripheral presentation of stimuli. Presenting stimuli in the periphery as is required in the tachistoscopic paradigm effectively activates the magnocellular pathway. This pathway is dominated by input from large receptive fields and specialized

for processing black and white contrast. These characteristics might present favorable conditions for the processing of large as opposed to small stimuli. Whether the magnocellular pathways are driving the bin effect can be examined by including a central presentation. At central presentation, foveal stimulation ensures the activation of the parvocellular pathways, pathways that are dominated by input from smaller receptive fields. If magnocellular activation is creating an advantage for processing large stimuli, then an opposite pattern should be seen for central presentations where an advantage should be observed for small stimuli.

*Main Effect of Frequency.*

Main effects of frequency consistently showed better performance under high frequency conditions which comes as little surprise given the difference in clarity. Augmentation of the topological task advantage under large bin conditions was noted suggesting that the determination of position was more difficult when the stimulus was blurry. This is in keeping with Ivry and Robertson (1998) who showed that under blurred conditions, the dot could not easily be distinguished from the line when presented in the nearest dot position. If the dot cannot be easily distinguished from the line, determinations of the dot's position relative to the line will be more difficult.

Although no four-way interactions emerged for male participants, at 100 ms a task x bin x frequency interaction showed that the high frequency advantage was consistent for both bin sizes when performing the topological task but no advantage was found for small bins when performing the metric task. In other words, performance of the metric task did not depend on stimulus clarity contrary to the reports of others (Sergeant, 1991; Okubo & Michimata, 2002). This has implications for the effect

predicted by two-process theory and found under comparable conditions to the small bin, high frequency conditions found here. The right hemisphere advantage for the metric task under small bin, high frequency conditions is not due to a high frequency advantage because under small bin, frequency has no meaningful effect. Rather the right hemisphere advantage for the metric task under small bin, high frequency conditions is attributable to a right hemisphere advantage for small bins when performing distance judgments. This is inconsistent with bin theory and suggests that the right hemisphere makes distance judgments using smaller excitatory centres when the stimulus is presented under high spatial frequency.

#### *Summary of Findings*

Initially, three possible explanations for Kosslyn's effect were posed. The first explanation was that the task x hemisphere interaction noted previously (Cowin & Hellige, 1994; Hellige & Michimata, 1989; Kosslyn et al., 1989; Rybash & Hoyer, 1992) was attributable to the mediation of an attentional mechanism that relayed input to the hemisphere that was specialized for processing the size of the stimulus that facilitated task completion. The second explanation was that asymmetry in spatial judgments was due to asymmetry in processing spatial frequencies. The last and more complicated explanation was that both stimulus size and spatial frequency impacted performance on the two spatial judgment tasks.

The double double dissociation was designed to both confirm one theory and disconfirm the other as the mechanism driving asymmetry in spatial judgment. However, because of difficulties meeting the assumptions underlying the test, the double double dissociation was not able to serve the purpose for which it was developed. Regardless

these results can speak to the mediation of spatial judgments under specific conditions. For male participants, after sufficient practice, under small bin, high frequency conditions, the right hemisphere advantage on the metric task is attributable to a right hemisphere advantage for processing input through small attentional bins. Given this, it might be argued that bin theory provides the best account of the mechanism driving asymmetry in spatial judgments. However, bin theory predicted a right hemisphere advantage for large bin processing not small. In short, while bin size influences asymmetry in spatial judgment it does not do so in the manner predicted by the theory.

The interpretation of the four-way interactions noted for female participants supports the latter explanation. Bin size and spatial frequency were shown to be related but not in the way that was anticipated; in other words, not in the way predicted by the assumption of inconsistency. Facilitation was noted between large bins and high spatial frequency that suggests a role for receptive field redundancy and backprojection models. Furthermore, this data suggests that this relationship is not only task dependent but also time dependent as well providing fodder for speculation about the plasticity of the spatiotemporal relationship between receptive field size and spatial frequency extraction.

In addition, the hemisphere advantages for task were shown to emerge only sporadically but in the anticipated directions when they did emerge. This lends credence to the predictability of the findings under limited stimulus input conditions. Moreover, the stimulus input characteristics do not interact in the same way with both tasks or with both hemispheres suggesting that the two-process effect is attributable to qualitatively different processing strategies.

### *Additional Effects*

In addition to theoretically relevant findings, several other findings are relevant. Although hypotheses were not presented regarding sex differences and block effects, these effects were not unanticipated. The findings in regard to sex difference and block effects will be discussed briefly.

#### *Sex Differences.*

No hypotheses were presented regarding sex differences. Interestingly, sex differences have not been routinely examined in studies investigating topological and metric spatial subsystems. The reason for this is not clear, particularly given that male participants are considered to be functionally more asymmetrical than female participants and are generally better at visuospatial tasks than female participants. Only once has sex differences been examined specifically using topological and metric judgments. Rybash and Hoyer (1992) found that the visuospatial advantage for male participants was limited to distance judgments and that female participants outperformed their male counterparts on the categorical task. Most other studies, however, have found no support for sex differences on these spatial judgments (Bruyer, Scailquin & Coibion, 1997; Hellige & Michimata, 1989; Kosslyn, Chabris, Marsolek, Jacobs & Koenig, 1995) or have not examined them (Kosslyn et al., 1989).

In the present study, sex interacted with hemisphere, bin and frequency at 150 ms and with block, task and bin at 100 ms with a significant difference between exposure durations as well. Clearly, gender has a considerable effect on performance of the tasks and on the performance of the hemispheres under particular input conditions. Future researchers are well-advised to consider the impact of sex effects on topological

and metric judgments and on the processing of input conditions.

### *Block Effects.*

Transience in the effects sought in the present studies was expected based on previous reports (Kosslyn et al., 1989) and because of the adaptive spatiotemporal properties of receptive fields. In the present studies, the block effects quite consistently showed better performance in the later trials suggesting that the effect was related to practice rather than fatigue. What is not clear is whether the performance noted in the second block of trials represented asymptote or whether linear improvement could be expected across the second block of trials as well. Indeed, the task x hemisphere effect predicted by two-process theory might reflect variation in the amount of practice required by the hemispheres to perform the tasks. Possibly the left hemisphere simply needs more practice to perform the metric task. What is clear, though, is that the inclusion of input condition manipulations made the task considerably more difficult essentially requiring at least 400 practice trials, substantially more than has been needed in studies without input condition manipulations.

### *Critical Questions Remaining*

Three critical methodological issues have been left unanswered. First, the lack of hemisphere x frequency interactions when unilateral viewing was ensured raises questions about the frequency manipulation. The attentional manipulation, that is presenting a bin size cue, might have inadvertently prepared the hemispheres for high frequency input because the cue was consistently presented at high spatial frequency. Selective attention has been shown to increase baseline neuronal activity and modulate

the sensitivity of neurons (Chawla, Rees & Friston, 1999), so it is possible that the increase in neuronal sensitivity might have tipped the scale in favor of high frequency conditions by sensitizing the receptive fields to high frequency input. If this is the case, the main effect of frequency could be attributed to the attentional manipulation rather than the frequency manipulation and the lack of hemisphere x frequency effects is explained. Whether the same main effect or whether hemisphere x frequency effects would have been found if the spatial frequency at which the attentional cues were presented had been matched to the spatial frequency of the stimuli remains a question for future study.

Second, although efforts were made to control the manipulation of spatial frequency and other input variables, not all stimulus characteristics could be tested and so perceptibility of the stimulus might have varied for large and small bin size and for high and low spatial frequency. For example, contrast could not be controlled due to technological limitations with the equipment, so clear stimuli were presented at a higher contrast than blurred stimuli. This difference in contrast might have made some stimuli more perceptible than others. In this way, general stimulus perceptibility might account for some of the asymmetries noted. Managing this confound is difficult but controlling contrast using a modulation transfer function (manipulating the luminance of the background screen and the luminance of the stimulus) would be one way of addressing this issue.

Finally, one of the difficulties with this work is that although bin size and spatial frequency were manipulated independently, at some level, they are known to exist in a dependent relationship that is governed by the laws of physics. The nature of this

relationship is unknown. Speculative computational models and neural networks provide useful frameworks for examination but have yet to bridge the gap between simulation and physiology. Examination of the spatiotemporal properties of receptive fields is a burgeoning area and likely a fruitful avenue for further exploration.

*Comments on the Double Double Dissociation*

Although the double double dissociation might offer a theoretically sound test of asymmetrically distributed input conditions using asymmetrically distributed tasks, the requisite four-way interaction and tests of assumptions proved to be very stringent pre-conditions to interpretation. The four-way interaction was a necessary but insufficient condition of the double double dissociation; necessary because a four-way interaction is theoretically predicted but insufficient for the very same reason. For example, bin is expected to vary by frequency in accordance with a mathematically articulated relationship. Both bin theory and spatial frequency theory predict asymmetrical processing of respective input conditions and two-process theory predicts asymmetrical task performance. So regardless of the direction of the double double dissociation, a four-way interaction is expected. The four-way interaction is, however, insufficient because the double double dissociation is built upon assumptions that create certain patterns of interaction within the four-way interaction. Theoretically, the double double dissociation should be interpretable if a pattern of task x hemisphere consistency and hemispheric inconsistency in input conditions emerges in the context of a four-way interaction. In the present data, where the four-way interaction emerged, task x hemisphere consistency could only be confirmed under the presumably consistent input conditions but verifying hemispheric consistency in input conditions was not possible in

light of a null finding in the hemisphere (task consistent) x conditions (hemispherically consistent) test.

Although ultimately, the double double dissociation was unable to dissociate bin theory from spatial frequency theory using metric and topological tasks, it does provide a possible framework for examining the effect of asymmetrically distributed input conditions on asymmetrically distributed tasks. Key to the success of the double double dissociation is to use tasks that have asymmetrical effects that are robust to variations in input conditions so that differences in performance between the inconsistent input condition combinations can be attributed to hemisphere differences and not singly to task advantages under one combination of input conditions. This might prove to be a more challenging task than it might seem particularly given that, as was shown in these studies, the hemisphere advantage for one task over another can interact with input conditions thereby changing the shape of the task x hemisphere interaction.

A similar difficulty can be described for the input conditions. Input conditions such as stimulus size and spatial frequency are dependent upon each other: neither can exist without the other. The nature of their interdependency might well vary according to task requirements. For example, judging relationships between objects under large bin conditions was facilitated when large stimuli were presented at high spatial frequency rather than low. In other words, the nature of the task appears to influence the optimum combination of input conditions regardless of the physics of the relationship.

The task advantages that arose as a result of input conditions and the impact of input condition combinations on hemispheric asymmetries in task performance were not anticipated and posed a significant challenge in interpreting the double double

dissociation. However, the four-way analysis was useful for deciphering the nature of the relationships between input characteristics, hemisphere asymmetries and task requirements. In other words, the double double dissociation analysis provided a means for examining the effects of three components of processing; those components being input characteristics, hemispheric asymmetry and task dependent processing all in a single design.

While it is argued that this design is a useful tool for examining the effect of asymmetrically processed input conditions on asymmetrically distributed tasks, this design fuels criticisms about fractionating approaches to cognitive neuroscience. The results here certainly suggest that asymmetrical processing is dependent not only on the tasks that are being performed but also on the input characteristics of the incoming stimuli, in effect, demonstrating that what happens in the black box is dependent on both input conditions and output demands.

## Post-script

This work represents the introduction of the double double dissociation test and an exploration of its application to examine one presiding question in the literature about spatial judgments. The double double dissociation is a method that is at least theoretically sound but, in the end, might prove to be of more academic interest than practical value due to the stringent assumptions on which it is based. That is not to say, however, that the method cannot be applied more successfully in a different context. But that is for others to examine.

Buoying this research was the additional ambition to further the important contributions to the study of high level visual processes that were made by Dr. S. Kosslyn and the late Dr. J. Sergeant. Although initially intended to put to rest the constructive volleys that waged between proponents of spatial frequency theory and supporters of bin theory, this work has confirmed that the relationship between tasks, hemispheres and input characteristics is rather more complicated than common methodology allows. In the spirit of antireductionism, the present findings might well form a springboard from which the complexities of visual processing can be observed, appreciated and indulged.

It must be human nature, I think, to seek elegant and inclusive solutions to the interminable vexations of human behavior. This work offers a structured method for examining the complexities of cognition, but in so doing, flies in the face of our need to dichotomize, dissociate, classify and simplify. Although we seek the most parsimonious explanations for our behavior, time and time again, we are proved to be the most enigmatic of creatures. It might be true in the end that the brain lacks sufficient capacity

to truly know itself. In the process of this work, I have developed a healthy appreciation for the plethora of challenges. To think across domains of form and function, physiology and cognition, principles and exceptions is a relentlessly consuming task. But perhaps most challenging of all is the need to simultaneously relinquish the comfort of encompassing interpretations and embrace the great possibilities held within the folds of trifling points.

## REFERENCES

- Angelucci, A., & Bullier, J. (2003). Reaching beyond the classical receptive field of V1 neurons: Horizontal or feedback axons? Journal of Physiology, *97*, 141-154.
- Badcock, J. C., Whitworth, F. A., Badcock, D. R., & Lovegrove, W. J. (1990). Low-frequency filtering and the processing of local-global stimuli. Perception, *19*, 617-629.
- Banich, M. T., & Federmeier, K. D. (1999). Categorical and metric spatial processes distinguished by task demands and practice. Journal of Cognitive Neuroscience, *11*(2), 153-166.
- Batt, V., Underwood, G., & Bryden, M. P. (1995). Inspecting asymmetric presentations of words differing in informational and morphemic structure. Brain and Language, *49*, 202 – 223.
- Bradshaw, G. J., Hicks, R. E., & Rose, B. (1979). Lexical discrimination and letter-string identification in the two visual fields. Brain and Language, *8*, 10-18.
- Bressloff, P. C., Cowan, J. D. (2002). A spherical model for orientation and spatial-frequency tuning in a cortical hypercolumn. Philosophical Transcript Royal Society London, *357*, 1643-1667.
- Bruyer, R. Scailquin, J., & Coibion, P. (1997). Dissociation between categorical and coordinate spatial computations: Modulation by cerebral hemispheres, task properties, mode of response, and age. Brain and Cognition, *33*, 245-277.
- Campbell, F. W., & Robson, J. G. (1968). Application of Fourier analysis to the visibility of gratings. Journal of Physiology, *197*, 551-566.
- Cave, K. R., & Kosslyn, S. M. (1989). Varieties of size-specific visual selection. Journal

of Experimental Psychology: General, 118(2), 148-164.

Chabris, C. F., & Kosslyn, S. M. (1998). How do the cerebral hemispheres contribute to encoding spatial relations. Current Directions in Psychological Science, 7(1), 8-14.

Chawla, D., Rees, G., & Friston, K. (1999). The physiological basis of attentional modulation in extrastriate visual areas. Nature Neuroscience, 2(7), 671-676.

Cook, N. D., Fruh, H., & Landis, T. (1995). The cerebral hemispheres and neural network simulations: Design considerations. Journal of Experimental Psychology: Human Perception and Performance, 21(2), 410-422.

Cowin, E. L., & Hellige, J. B. (1994). Categorical versus coordinate spatial processing: Effects of blurring and hemispheric asymmetry. Journal of Cognitive Neuroscience, 6(2), 156-164.

Christman, S. (1990). Effects of luminance and blur on hemispheric asymmetries in temporal integration. Neuropsychologia, 28(4), 361-374.

Christman, S., Kitterle, F. L., & Hellige, J. (1991). Hemispheric asymmetry in the processing of absolute versus relative spatial frequency. Brain and Cognition, 16, 62-73.

Davis, E. T., & Graham, N. (1981). Spatial frequency uncertainty effects in the detection of sinusoidal gratings. Vision Research, 21, 705-712.

De Valois, R. L., Albrecht, D. G., & Thorell, L. G. (1982). Spatial frequency selectivity of cells in macaque visual cortex. Vision Research, 22, 545-559.

De Valois, R. L., Morgan, H., & Snodderly, D. M. (1974). Psychophysical studies of monkey vision-III. Spatial luminance contrast sensitivity tests of macaque and

- human observers. Vision Research, 14, 75-81.
- Eriksen, C. W., & Schultz, D. W. (1977). Retinal locus and acuity in visual information processing. Bulletin of the Psychonomic Society, 9(2), 81-84.
- Flavell, J. H., & Draguns, J. (1957). A microgenetic approach to perception and thought. Psychological Bulletin, 54(3), 197-217.
- Goldstein, E. B. (1996). Sensation and Perception (4<sup>th</sup> ed.). New York, NY: Thomson Publishing Company.
- Hellige, J. B., & Michimata, C. (1989). Categorization versus distance: Hemispheric differences for processing spatial information. Memory and Cognition, 17(6), 770-776.
- Hubel D. H., & Wiesel, T. N. (1977). Functional architecture of macaque monkey visual cortex. Proceedings of the Royal Society of London, 198, 1-59.
- Ivry, R. B., & Robertson, L. C. (1998). The Two Sides of Perception. MIT Press: Cambridge, MA.
- Jager, G., & Postma, A. (2003). On the hemispheric specialization for categorical and coordinate spatial relations: A review of the current evidence. Neuropsychologia, 41, 504-515.
- James, W. (1913). Psychology. New York: Henry Holt & Company. (Original work published 1892)
- Kitterle, F. L., Christman, S., Conesa, J. (1993). Hemispheric differences in the interference among components of compound gratings. Perception & Psychophysics, 54(6), 785-793.
- Kitterle, F. L., Hellige, J. B., & Christman, S. (1992). Visual hemispheric asymmetries

depend on which spatial frequencies are task relevant. Brain and Cognition, 20, 308-314.

Kosslyn, S. M. (1987). Seeing and imagining in the cerebral hemispheres: A computational approach. Psychological Review, 94(2), 148-175.

Kosslyn, S. M. (1995). On computational evidence for different types of spatial relations encoding: Reply to Cook et al. (1995). Journal of Experimental Psychology: Human Perception and Performance, 21(2), 423-431.

Kosslyn, S. M., Anderson, A. K., Hillger, L. A., & Hamilton, S. E. (1994). Hemispheric differences in sizes of receptive fields or attentional biases? Neuropsychology, 8(2), 139-147.

Kosslyn, S. M., Chabris, C.F., Marsolek, C. J., Koenig, O. (1992). Categorical versus coordinate spatial relations: Computational analyses and computer simulations. Journal of Experimental Psychology, 18, 562-577.

Kosslyn, S. M., Koenig, O., Barrett, A., Cave, C. B., Tang, J., & Gabrieli, J. D. E. (1989). Evidence for two types of spatial representations: Hemispheric specialization for categorical and coordinate relations. Journal of Experimental Psychology: Human Perception and Performance, 15(4), 721-735.

Kosslyn, S. M., Flynn, R. A., Amsterdam, J. B., & Wang, G. (1990). Components of high-level vision: A cognitive neuroscience analysis and accounts of neurological syndromes. Cognition, 34, 203-277.

Kosslyn, S.M., Thompson, W. L., Gitelman, D. R., & Alpert, N. M. (1998). Neural systems that encode categorical versus coordinate spatial relations: PET investigations. Psychobiology, 26(4), 333-347.

- Laeng, B., Shah, J., & Kosslyn, S., (1999). Identifying objects in conventional and contorted poses: contributions of hemisphere-specific mechanisms. Cognition, 10, 53-85.
- Lamme, V., Super, H., & Spekreijse, H. (1998). Feedforward, horizontal, and feedback processing in the visual cortex. Current Opinion in Neurobiology, 8, 529 – 535.
- Mareschal, I., Henrie, J. A., & Shapley, R. M. (2002). A psychophysical correlate of contrast dependent changes in receptive field properties. Vision Research, 42, 1879 - 1887
- Michimata, C., & Hellige, J. B. (1987). Effects of blurring and stimulus size on the lateralized processing of nonverbal stimuli. Neuropsychologia, 25(2), 397-407.
- Mihaylova, M., Stomonyakov, V., & Vassilev, A. (1999). Peripheral and central delay in processing high spatial frequencies: Reaction time and VEP latency studies. Vision Research, 39, 699 – 705.
- McGraw, P. V., Levi, D. M., & Whitaker, D. (1999). Spatial characteristics of the second-order visual pathway revealed by positional adaptation. Nature Neuroscience, 2(5), 479-484.
- Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. Science, 29, 782-784.
- Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. Cognitive Psychology, 9, 353-383.
- Nicholls, M. E. R., & Atkinson, J. (1993). Hemispheric asymmetries for an inspection time task: A general left hemisphere temporal advantage? Neuropsychologia, 31(11), 1181-1190.

- Nicholls, M. E. R., & Cooper, C. J. (1991). Hemispheric differences in the rates of information processing for simple non-verbal stimuli. Neuropsychologia, *29*(7), 677-684.
- Nicholls, M. E. R., & Whelan, R. E. (1998). Hemispheric asymmetries for the temporal resolution of brief tactile stimuli. Journal of Clinical and Experimental Neuropsychology, *20*(4), 445-456.
- Niebauer, C. L., Christman, S. D. (1998). Upper and lower visual field differences in categorical and coordinate judgments. Psychonomic Bulletin & Review, *5*(1), 147-151.
- Okubo, M., & Michimata, C. (2002). Hemispheric processing of categorical and coordinate spatial relations in the absence of low spatial frequencies. Journal of Cognitive Neuroscience, *14*(2), 291-297.
- O'Reilly, R. C., Kosslyn, S. M., Marsolek, C. J., & Chabris, C. F. (1990). Receptive field characteristics that allow parietal lobe neurons to encode spatial properties of visual input: A computational analysis. Journal of Cognitive Neuroscience, *2*(2), 141-155.
- Parrot, M., Doyon, B., Demonet, J-F., & Cardebat, D. (1999). Hemispheric preponderance in categorical and coordinate visual processes. Neuropsychologia, *37*, 1215-1225.
- Pasternak, T., & Merigan, W. H. (1981). The luminance dependence of spatial vision in the cat. Vision Research, *21*, 1333-1339.
- Plainis, S., & Murray, I. J. (2000). Neurophysiological interpretation of human visual reaction times: Effect of contrast, spatial frequency and luminance.

- Neuropsychologia, 38, 1555-1564.
- Pring, T. R. (1981). The effect of stimulus size and exposure duration on visual field asymmetries. Cortex, 17, 227-240.
- Rao, R., & Ballard, D. (1999). Predictive coding in the visual cortex: A functional interpretation of some extra-classical receptive-field effects. Nature Neuroscience, 2(1), 79-87.
- Rybash, J. M., & Hoyer, W. J. (1992). Hemispheric specialization for categorical and coordinate spatial representations: A reappraisal. Memory and Cognition, 20(3), 271-276.
- Sandler, A. J., & Deary, I. J. (1996). Cerebral asymmetries in inspection time? Neuropsychologia, 34(4), 283-295.
- Sceniak, M., Ringach, D., Hawken, M., & Shapley, R. (1999). Contrast's effect on spatial summation by macaque V1 neurons. Nature Neuroscience, 2(8), 733-739.
- Sergent, J. (1982a). The cerebral balance of power. Journal of Experimental Psychology: Human Perception and Performance, 8(2), 253-272.
- Sergent, J. (1982b). Theoretical and methodological consequences of variations in exposure duration in visual laterality studies. Perception and Psychophysics, 31(5), 451-461 .
- Sergent, J. (1982c). Influence of luminance on hemispheric processing. Bulletin of the Psychonomic Society, 20(4), 221-223.
- Sergent, J. (1983a). Role of the input in visual hemispheric asymmetries. Psychological Bulletin, 93(3), 481-512.
- Sergent, J. (1983b). The effects of sensory-limitations on hemispheric processing.

- Canadian Journal of Psychology, 37(3), 345-366.
- Sergent, J. (1983c). Influence of luminance on hemispheric processing. Bulletin of the Psychonomic Society, 20(4), 221-223.
- Sergent, J. (1984). Role of contrast, lettercase, and viewing conditions in a lateralized word-naming task. Perception and Psychophysics, 35(5), 489-498.
- Sergent, J. (1987). Failures to confirm the spatial-frequency hypothesis: Fatal blow or healthy complication? Canadian Journal of Psychology, 41(4), 412-428.
- Sergent, J. (1991). Judgments of relative position and distance on representations of spatial relations. Journal of Experimental Psychology: Human Perception and Performance, 91(3), 762-780.
- Sergent, J., & Hellige, J. B. (1986). Role of input factors in visual-field asymmetries. Brain and Cognition, 5, 174-199.
- Shulman, G. L., Sullivan, M. A., Gish, K., & Sakoda, W. J. (1986). The role of spatial-frequency channels in the perception of local and global structure. Perception, 15, 259-273.
- Smith, A. T., Singh, K. D., Williams, A. L., & Greenlee, M. W. (2001). Estimating receptive field size from fMRI data in human striate and extrastriate visual cortex. Cerebral Cortex, 11, 1182 – 1190.
- Taylor, A. T., & Hellige, J. B. (1987). Effects of retinal size on visual laterality. Bulletin of the Psychonomic Society, 25(6), 444-446.
- Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. Cognitive Psychology, 12, 97-136.
- Trojano, L., Grossi, D., Linden, D., Formisano, E., Goebel, R., Cirillo, S., Elefante, R.,

- & Di Salle, F. (2002). Coordinate and categorical judgments in spatial imagery. *Neuropsychologia*, 40, 1666-1674.
- Ungerleider, L. G., & Mishkin, M. (1982). Two cortical visual systems. In D.J. Ingle, M. A. Goodale, & R. J. W. Mansfield (Eds.), *Analysis of visual behavior*. Cambridge, MA: MIT Press.
- Vassilev A., & Mitov, D., (1976). Perception time and spatial frequency. *Vision Research*, 16, 89-92.
- Weisstein, N. (1980). The joy of Fourier analysis. In C. S. Harris (Ed.), *Visual Coding and Adaptability*. Hillsdale, NJ: Lawrence Erlbaum Associates.
- Wilkinson, D., & Donnelly, N. (1999). The role of stimulus factors in making categorical and coordinate spatial judgments. *Brain and Cognition*, 39, 171-185.
- Wortgotter, F., Suder, K., Zhao, Y., Kerscher, N., Eysel, U. & Funke, K. (1998). State-dependent receptive-field restructuring in the visual cortex. *Nature*, 396, 165-168.

## Appendix A: Ethics Approval, Consent Form and Debriefing



### UNIVERSITY ADVISORY COMMITTEE ON ETHICS IN BEHAVIOURAL SCIENCE RESEARCH

**NAME:** Lorin J. Elias, (Psychology)  
K. Goodall

**BSC#:** 2001-235

**DATE:** 15-Jan-2002

The University Advisory Committee on Ethics in Behavioural Science Research has reviewed the Application for Ethics Approval for your study: "The Attentional Window: Bin Regulator or Frequency Filter?" (2001-235).

1. Your study has been APPROVED subject to the following modification(s) to your consent form:
  - Add a line to the effect that the research has been approved by the University of Saskatchewan Advisory Committee on Ethics in Behavioural Sciences Research on (insert date).
  - Modify your withdrawal statement to read "...without penalty of any type, and without loss of credit for the session."
2. Please send one copy of your revisions to the Office of Research Services for our records. Please highlight or underline any changes made when resubmitting.
3. This letter serves as your certificate of approval, effective as of the time that you have completed the requested modifications. If you require a letter of unconditional approval, please so indicate on your reply, and one will be issued to you. Any significant changes to your proposed study should be reported to the Chair for Committee consideration in advance of its implementation.
4. This approval is valid for five years on the condition that a status report form is submitted annually to the Chair of the Committee. This certificate will automatically be invalidated if a status report form is not received within one month of the anniversary date. Please refer to the website for further instructions: <http://www.usask.ca/research/ethics.shtml>

I wish you a successful and informative study.

  
Valerie Thompson  
Chair, University Advisory Committee  
on Ethics in Behavioural Science Research

Office of Research Services, University of Saskatchewan  
Kirk Hall Room 210, 117 Science Place, Saskatoon SK S7N 5C8 CANADA  
Telephone: (306) 966-8576 or (306) 966-2084 Facsimile: (306) 966-8597 <http://www.usask.ca/research/>

## CONSENT FORM

### Judgment of Dot Location under Directed Attention

**Researchers:** Kate Goodall, Department of Psychology, phone: 966-6699

Dr. L. Elias, Department of Psychology, phone: 966-6670

**Purpose and objectives of the study:** The purpose of this study is to examine how each half of the brain pays attention during a dot location task. Some researchers say that depending on what task the brain must perform, the brain divides the visual scene into large and small areas and the hemispheres are different in how well they do this. Other researchers say that the brain pays attention to a task by selecting the kind of light waves that provide the information needed to perform a task. Again, they say that the halves of the brain are better at processing different kinds of light waves. This study attempts to determine how the brain pays attention during a dot location task and whether the two halves of the brain do this differently.

**Possible benefits of the study:** This project provides you with the opportunity to learn about some of the properties of attention in the visual system. You will gain experience with experimental psychology and be given the chance to learn of the results of the study (only group results will be released).

**Procedure:** After consenting to participate, you will be asked to complete a brief handedness questionnaire. You will then be asked to view images flashed quickly on a computer screen in a darkened room. Your task is to judge whether a small dot is located above or below or more or less than 3 mm from a given reference point. You will be told when to make which kind of judgment. You will respond by speaking clearly into a microphone. Some pictures will be clear and others will be blurry. The microphone does not record you but simply stops the timer in the computer.

**Possible risks:** There are no known risks associated with this procedure.

I, \_\_\_\_\_, have read the above description and agree to participate. The procedure and possible risks have been explained to me by the researcher, and I understand them. I understand that I am free to withdraw from this study at any time without penalty of any type and without losing credit for participating. I also understand that although the data from this study might be published in a research article, only group data will be described and my identity will be kept confidential. I also confirm that I have received a copy of this consent form for my records.

\_\_\_\_\_  
(signature)

\_\_\_\_\_  
(date)

\_\_\_\_\_  
(researcher) Department of Psychology, University of Saskatchewan

---

If you have any concerns about this study or your rights as a participant, please contact the Office of Research Services (306) 966-4053

## Judgment of Dot Location under Directed Attention

Thank you for participating in this study! Your brain has two hemispheres, one on the left and one on the right. We know that each hemisphere is specialized for performing certain tasks. For example, the left hemisphere is usually better at verbal tasks, and the right hemisphere is usually better at non-verbal tasks. When it comes to judging dot location, previous research has found that the left hemisphere is somewhat better at performing category judgments like “above/below” and the right hemisphere is usually better at performing distance judgments like “more/less than”.

What is not clear is how our brain pays attention to a task and whether our hemispheres use different strategies to pay attention. One theory, Bin Theory, is that when you pay attention to something you see, your brain is dividing the visual scene into pockets of space that are the right size for processing the thing that you are looking at. This theory further states that the left hemisphere is better at dividing a scene into small pockets whereas the right hemisphere is better at dividing the scene into large pockets. In this study, when you were cued with a large circle, your brain was attending to a large pocket. But when you were cued for the bar, your brain was attending to a small pocket.

Another attention theory, Spatial Frequency Theory, states that when you pay attention to a task, your brain is filtering out the light waves that are not helpful for doing the task and allowing only those light waves that are helpful to pass through for further processing. This theory further states that the right hemisphere is better at processing low frequency light waves and the left hemisphere is better at processing high frequency light waves. When the stimuli were blurry, low frequency information was being offered, but when the stimuli were clear, high frequency information was being offered.

The trick here is to provide information to only one half of the brain and not the other. When the dot pictures are flashed quickly on the left side of the screen, only the right half of your brain gets the visual picture. Similarly, when the dot pictures are flashed quickly on the right side of the screen, only the left half of your brain gets the picture. So, we are able to figure out which side of your brain is performing the location task more quickly and more accurately under a particular type of attention.

If Bin Theory is the right theory, we should see that the frequency of the light waves had no effect and that the right hemisphere was faster than the left at making distance judgments when cued for a big pocket and the left hemisphere was faster than the right at making above/below judgments when cued for a small pocket. If Spatial Frequency Theory is correct, we should see that the cue for pocket size had no effect and that the right hemisphere was faster than the left at making distance judgments when the picture was blurry and the left hemisphere was faster than the right when making above/below judgments when the picture was clear.

If you wish to see a copy of our final results, please leave your name and address with one of the researchers or contact either K. Goodall at 966-6699 or Dr. L. Elias at 966-6670.



16. Is there any reason (e.g., injury) why you have changed your hand preference for any of the above activities? YES NO
17. Have you been given special training or encouragement to use a particular hand for certain activities? YES NO
18. If you have answered YES to either Questions 16 or 17, please explain.

---

**Instructions:** Please indicate your foot preference for the following activities by circling the appropriate response. If you **always** (i.e., 95% or more of the time) use one foot to perform the described activity, circle **Ra** or **La** (for **right always** or **left always**). If you **usually** (i.e., about 75% of the time) use one foot circle **Ru** or **Lu**, as appropriate. If you use both feet **equally often** (i.e., you use each hand about 50% of the time), circle **Eq**. Please do not simply circle one answer for all questions, but imagine yourself performing each activity in turn, and then mark the appropriate answer.

- |   |    |    |    |     |    |
|---|----|----|----|-----|----|
| 19. Which foot would you use to kick a stationary ball at a target straight ahead?  | La | Lu | Eq | Ru  | Ra |
| 20. If you had to stand on one foot, which foot would it be?  | La | Lu | Eq | Ru  | Ra |
| 21. Which foot would you use to smooth sand at the beach?   | La | Lu | Eq | Ru  | Ra |
| 22. If you had to step up onto a chair, which foot would you place on the chair first?  | La | Lu | Eq | Ru  | Ra |
| 23. Which foot would you use to stomp on a fast-moving bug?   | La | Lu | Eq | Ru  | Ra |
| 24. If you were to balance on one foot on a railway track, which foot would you use?  | La | Lu | Eq | Ru  | Ra |
| 25. If you wanted to pick up a marble with your toes, which foot would you use?   | La | Lu | Eq | Ru  | Ra |
| 26. If you had to hop on one foot, which foot would you use?  | La | Lu | Eq | Ru  | Ra |
| 27. Which foot would you use to help push a shovel into the ground?   | La | Lu | Eq | Ru  | Ra |
| 28. During relaxed standing, most people have one leg fully extended for support and the other slightly bent. Which leg do you have fully extended first? | La | Lu | Eq | Ru  | Ra |
| 29. Is there any reason (i.e. injury) why you have changed your foot preference for any of the above activities?  |    |    |    | Yes | No |
| 30. Have you ever been given special training or encouragement to use a particular foot for certain activities?   |    |    |    | Yes | No |
| 31. If you have answered YES for either question 29 or 30, please explain:  |    |    |    |     |    |

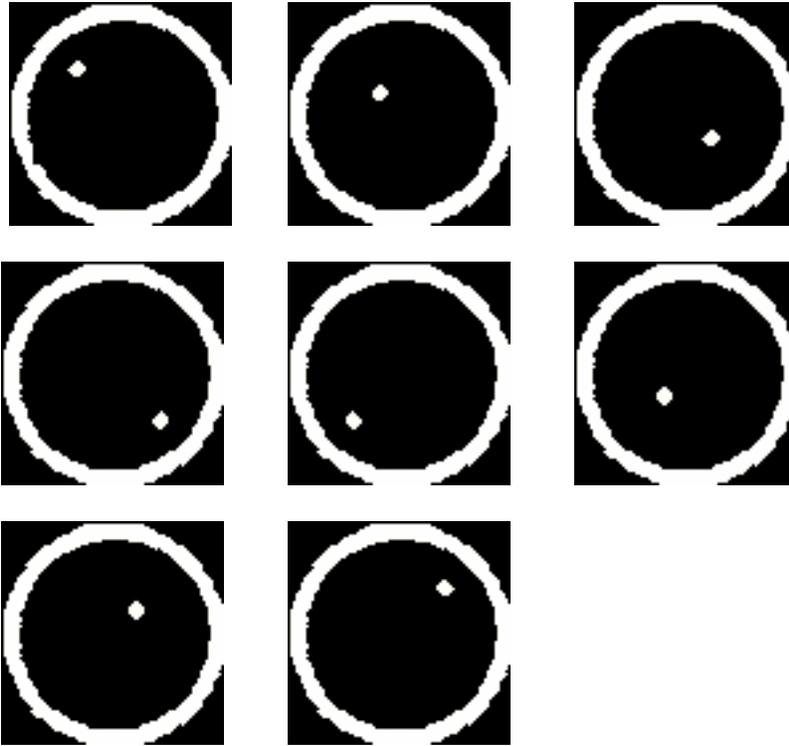
---

The experimenter will complete question 32:

---

## Appendix C

### i. Circle and Dot stimuli for the First Pilot Study



ii. ANOVA Table for the First Pilot Study, Task x Hemisphere, Reaction Time, Central Reference

Source	df	F
		Reaction Time
Within subjects		
Task (T)	1	0.031
Hemisphere (H)	1	0.769
T x H	1	0.020
T x H within-group		
error	8	(4034.905)

Note. Values enclosed in parentheses are mean square errors (MSE).

\* $p < .05$

iii. ANOVA Table for the First Pilot Study, Task x Hemisphere, Reaction Time,  
Peripheral Reference

		<i>F</i>
Source	<i>df</i>	Reaction Time
Within subjects		
Task (T)	1	0.625
Hemisphere (H)	1	0.269
T x H	1	0.125
T x H within-group		
error	8	(3461.540)

Note. Values enclosed in parentheses are mean square errors (MSE).

\* $p < .05$

iv. ANOVA Table for the First Pilot Study, Task x Hemisphere, Accuracy, Central Reference

Source	df	F	
		Percent Correct	
Within subjects			
Task (T)	1	4.975*	
Hemisphere (H)	1	0.702	
T x H	1	2.221	
T x H within-group error	9	(0.001)	

Note. Values enclosed in parentheses are mean square errors (MSE).

\* $p < .05$

v. ANOVA Table for the First Pilot Study, Task x Hemisphere, Accuracy, Peripheral Reference

Source	df	F	
		Percent Correct	
Within subjects			
Task (T)	1	120.496**	
Hemisphere (H)	1	0.245	
T x H	1	1.507	
T x H within-group error	9	(0.002)	

Note. Values enclosed in parentheses are mean square errors (MSE).

\* $p < .05$ ; \*\* $p < .001$

vi. Mean Reaction Time (Standard Deviation) and Accuracy (Standard Deviation) Data for the First Pilot for all Variables ( $n = 10$ ).

Variable			RT( <i>SD</i> )	Acc.( <i>SD</i> )
Task	Reference Point	Hemisphere		
Topological	Central	Right	776(181)	.91(0.09)
		Left	796(234)	.91(0.07)
	Peripheral	Right	836(221)	.53(0.06)
		Left	787(133)	.54(0.04)
Metric	Central	Right	759(245)	.88(0.07)
		Left	785(202)	.85(0.09)
	Peripheral	Right	769(238)	.84(0.08)
		Left	764(178)	.82(0.11)

Note. RT = Reaction time. *SD* = Standard deviation. Acc. = Accuracy

## Appendix D

### i. ANOVA Table for the Second Pilot Study, Task x Hemisphere, Reaction Time

Source	<i>df</i>	<i>F</i>
		Reaction time
Within subjects		
Task (T)	1	81.073**
Hemisphere (H)	1	5.997*
T x H	1	7.136*
T x H within-group		
error	15	(448.193)

Note. Values enclosed in parentheses are mean square errors (MSE).

\* $p < .05$ ; \*\* $p < .001$

ii. ANOVA Table for the Second Pilot Study, Task x Hemisphere, Accuracy

Source	<i>df</i>	<i>F</i>
		Percent Correct
Within subjects		
Task (T)	1	15.393**
Hemisphere (H)	1	4.516*
T x H	1	2.618
T x H within-group		
Error	15	(<0.001)

Note. Values enclosed in parentheses are mean square errors (MSE).

\* $p < .05$

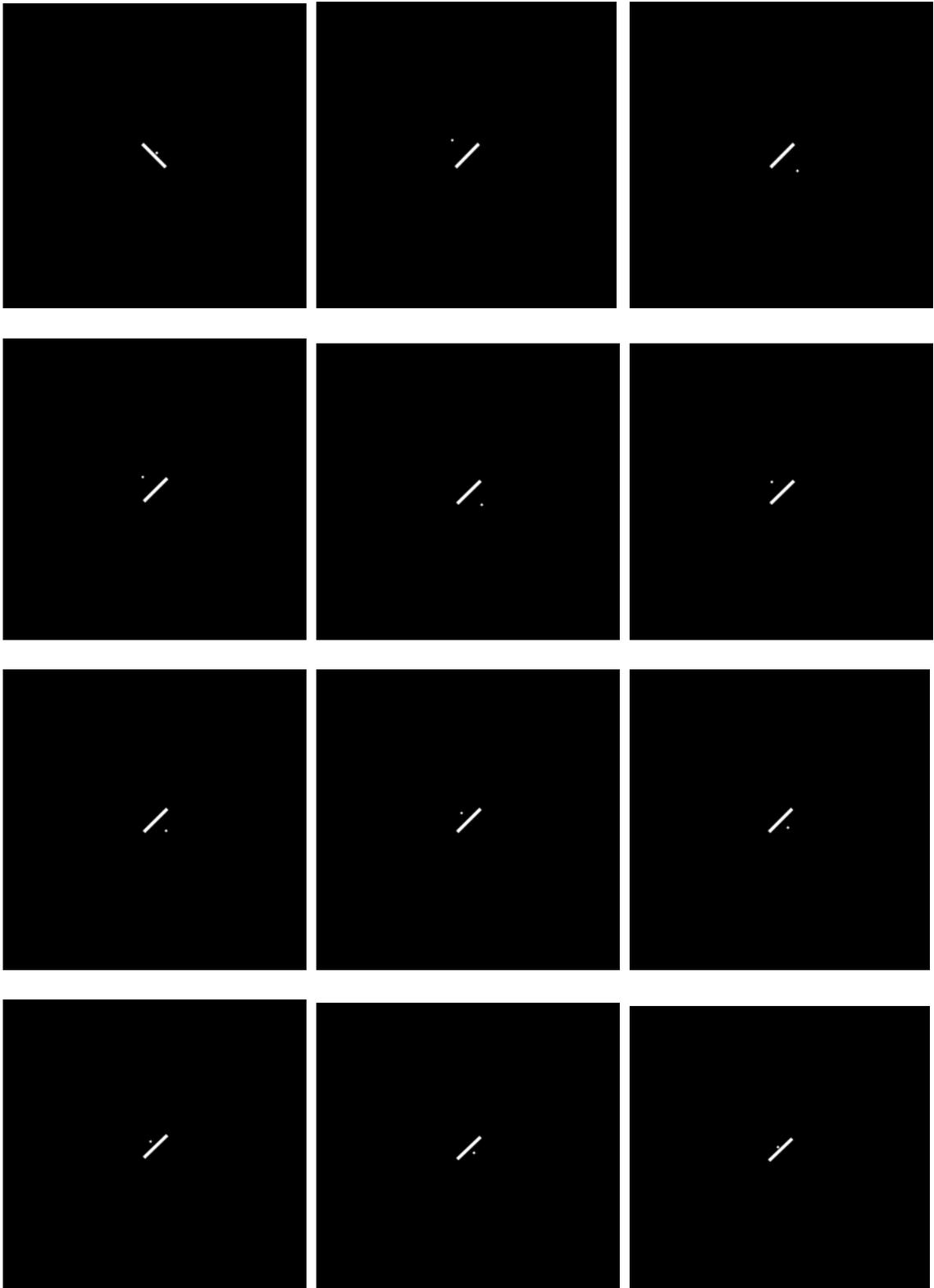
iii. *Mean Reaction Time (Standard Deviation) and Accuracy (Standard Deviation) Data for the Second Pilot for all Variables (n = 16).*

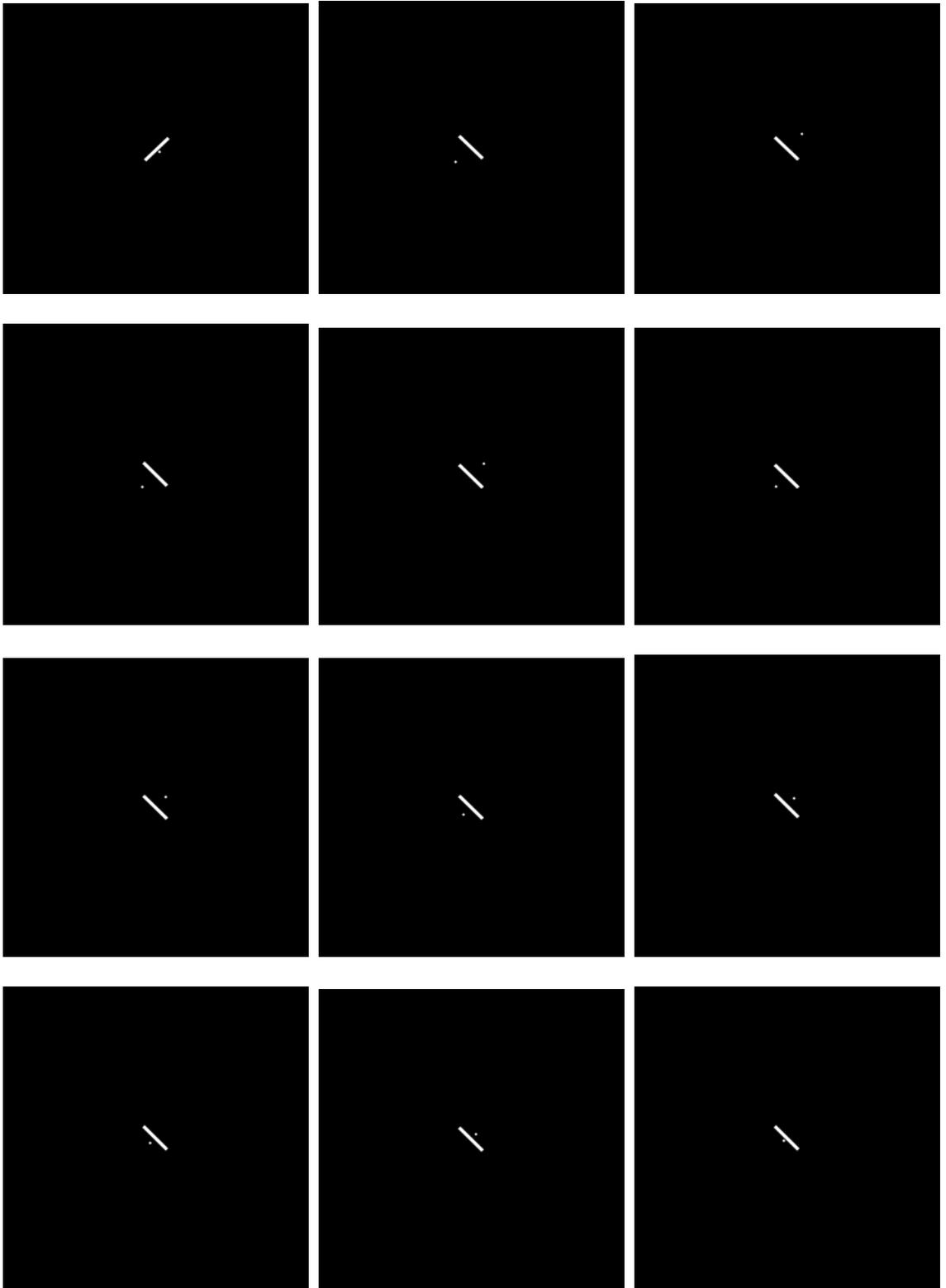
Variable		RT( <i>SD</i> )	Acc.( <i>SD</i> )
Task	Hemisphere		
Topological	Right	428(93)	.98(0.01)
	Left	426(92)	.98(0.02)
Metric	Right	589(110)	.85(0.14)
	Left	618(141)	.83(0.14)

Note. RT = Reaction time. *SD* = Standard deviation. Acc. = Accuracy.

Appendix E

i. Bar and Dot Stimuli for the Final Pilot Study





ii. ANOVA Table for the Final Pilot Study, Between Groups, Task x Hemisphere,  
Reaction Time

Source	df	F
		Reaction time
Between subjects		
<i>Main Effects</i>		
Stimulus Orientation (SO)	1	2.695
SO between-group		
error	22	(34263.442)
<i>Two-way Interactions</i>		
SO x Task (T)	1	20.160**
T within-group		
error	22	(5410.083)
SO x Hemisphere (H)	1	12.550*
H within-group		
error	22	(498.555)
<i>Three-way Interactions</i>		
SO x T x H	1	2.024
T x H within-group		
error	22	(418.664)

---

Within subjects		
T	1	50.467**
H	1	0.479
T x H	1	4.604*
T x H within-group		
error	22	(418.664)

---

Note. Values enclosed in parentheses are mean square errors (MSE).

\* $p < .05$ ; \*\* $p < .001$

iii. ANOVA Table for the Final Pilot Study, Between Groups, Task x Hemisphere,  
Accuracy

Source	df	F
		Reaction time
Between subjects		
<i>Main Effects</i>		
Stimulus Orientation (SO)	1	0.990
SO between-group error	24	(0.014)
<i>Two-way Interactions</i>		
SO x Task (T)	1	1.982
SO x T within-group Error	24	(0.016)
SO x Hemisphere (H)	1	0.459
SO x H within-group Error	24	(0.001)
<i>Three-way Interactions</i>		
SO x T x H	1	0.313
SO x T x H within-group Error	24	(0.001)

---

Within subjects		
T	1	17.471**
H	1	3.407
T x H	1	1.474
T x H within-group		
Error	24	(0.001)

---

Note. Values enclosed in parentheses are mean square errors (MSE).

\* $p < .05$ ; \*\* $p < .001$

iv. ANOVA Table for the Final Pilot Study, Within Subjects, Task x Hemisphere,

Reaction Time

Source	<i>df</i>	<i>F</i>	
		Reaction time	
Within subjects			
Task (T)	1		2.907
Hemisphere (H)	1		6.051*
T x H	1		0.250
T x H within-group			
Error	9		(376.011)

Note. Values enclosed in parentheses are mean square errors (MSE).

\* $p < .05$

v. ANOVA Table for the Final Pilot Study, Within Subjects, Task x Hemisphere,

Accuracy

Source	<i>df</i>	<i>F</i>
		Percent Correct
Within subjects		
Task (T)	1	6.653*
Hemisphere (H)	1	0.464
T x H	1	0.124
T x H within-group		
error	9	(0.001)

Note. Values enclosed in parentheses are mean square errors (MSE).

\* $p < .05$

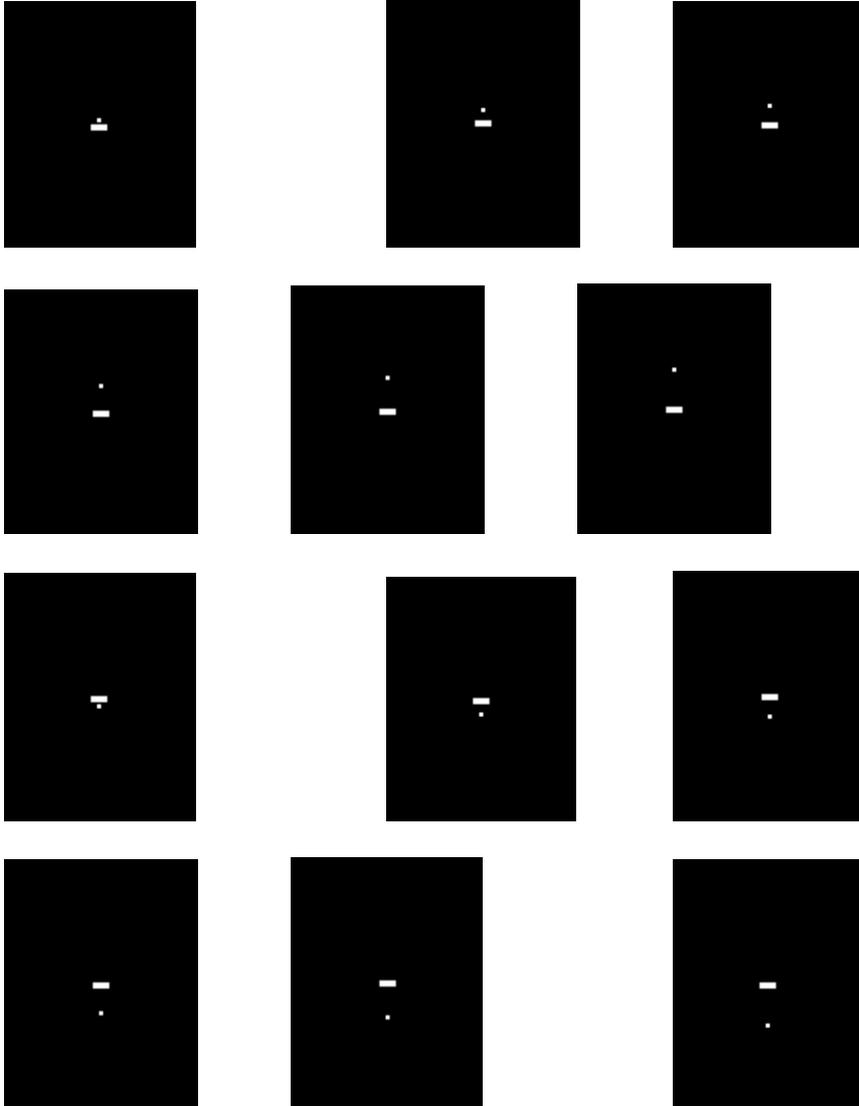
vi. Mean Reaction Time (Standard Deviation) and Accuracy (Standard Deviation) Data for the Final Pilot, Within Subjects for All Variables ( $n = 11$ ).

Variable			RT( <i>SD</i> )	Acc.( <i>SD</i> )
Task	Hemisphere			
Topological	Right	Rotated	570(101)	.94(0.04)
	Left	Rotated	545(79)	.94(0.04)
Metric	Right	Rotated	617(88)	.87(0.08)
	Left	Rotated	595(68)	.86(0.07)

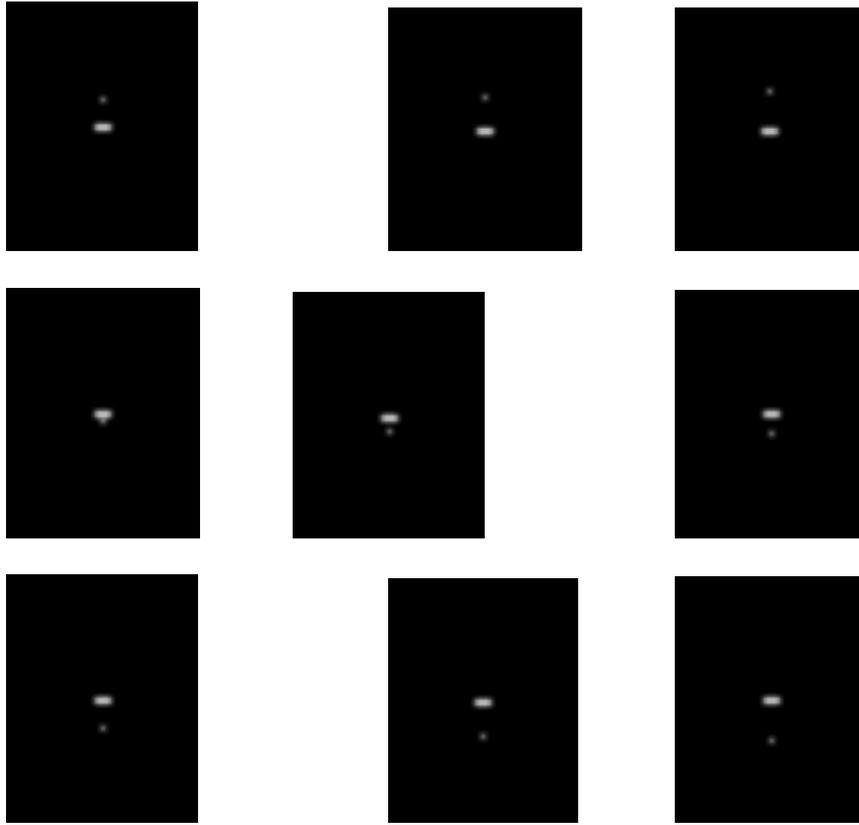
Note. RT = Reaction time. *SD* = Standard Acc. = Accuracy.

## Appendix F

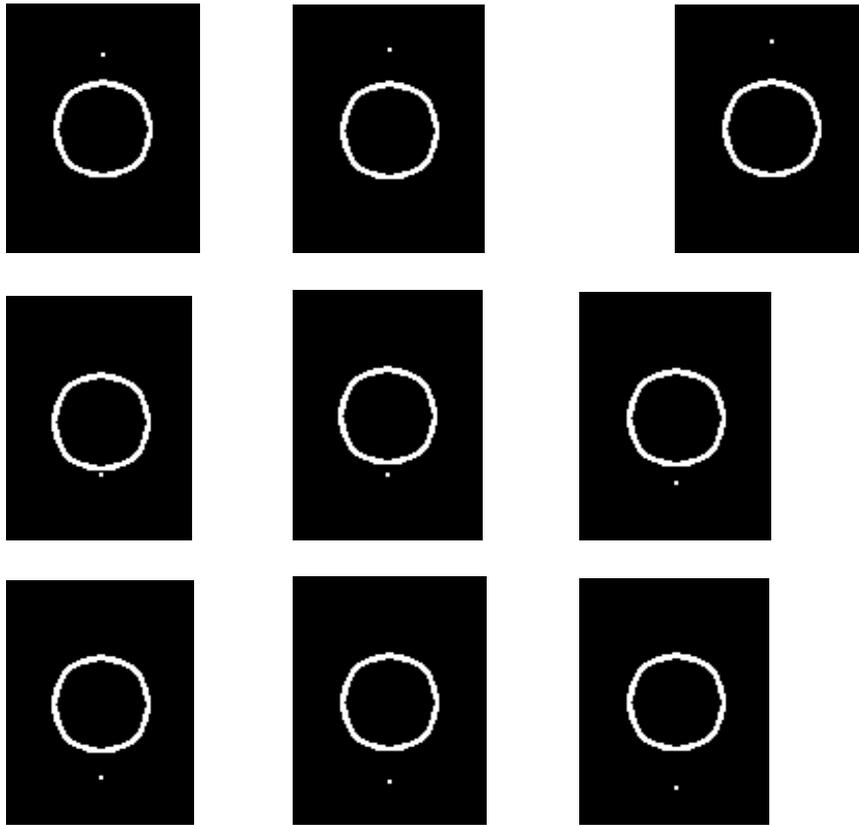
### i. Clear Bar and Dot Stimuli.



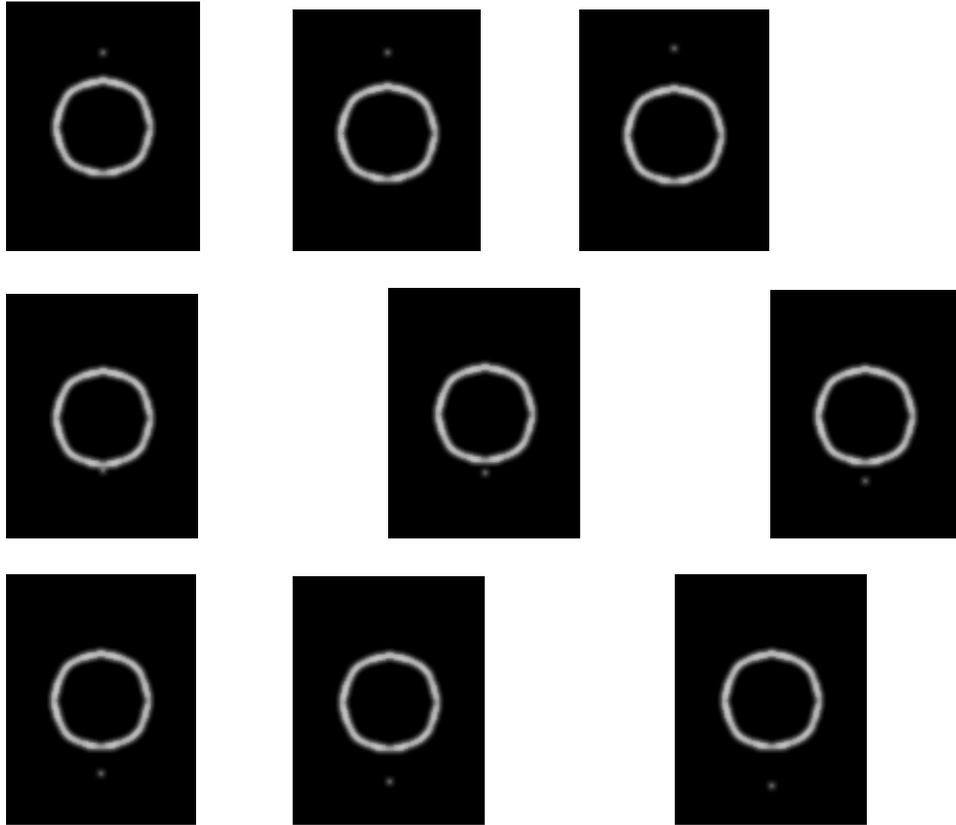
ii. Blurred Bar and Dot Stimuli



iii. Clear Circle and Dot Stimuli.



iv. Blurred Circle and Dot Stimuli.



## Appendix G

*i. Mean Reaction Time (Standard Deviation) and Accuracy (Standard Deviation) Data for all Variables (n = 65).*

Variable				RT( <i>SD</i> )	Acc.( <i>SD</i> )
Task	Hemisphere	Bin	Frequency		
			Block 1		
Metric	Right	Large	High	583(125)	.86(0.08)
			Low	590(116)	.86(0.09)
		Small	High	590(135)	.87(0.09)
			Low	594(127)	.84(0.10)
	Left	Large	High	576(119)	.87(0.08)
			Low	586(131)	.84(0.08)
		Small	High	589(136)	.85(0.09)
			Low	594(128)	.85(0.09)
Topological	Right	Large	High	417(84)	.99(0.03)
			Low	440(86)	.96(0.04)
		Small	High	449(89)	.98(0.03)
			Low	458(98)	.95(0.05)
	Left	Large	High	414(83)	.99(0.02)
			Low	428(83)	.97(0.05)
		Small	High	442(85)	.98(0.04)

			Low	460(91)	.95(0.05)
<hr/>					
			Block 2		
Metric	Right	Large	High	531(116)	.89(0.07)
			Low	538(111)	.88(0.08)
		Small	High	537(108)	.88(0.08)
			Low	539(112)	.84(0.09)
	Left	Large	High	530(110)	.89(0.07)
			Low	537(111)	.86(0.07)
		Small	High	539(118)	.86(0.08)
			Low	538(120)	.86(0.08)
Topological	Right	Large	High	395(78)	.99(0.02)
			Low	408(83)	.97(0.04)
		Small	High	418(78)	.98(0.03)
			Low	431(86)	.96(0.05)
	Left	Large	High	386(77)	.99(0.01)
			Low	405(86)	.97(0.04)
		Small	High	414(80)	.99(0.03)
			Low	425(87)	.96(0.05)

Note. RT = Reaction time. *SD* = Standard. Acc. = Accuracy

## Appendix H

### i. Shapiro-Wilks t Statistics for all Variables ( $df = 55$ )

Variable				Block 1	Block 2	
Task	Hemisphere	Bin	Frequency			
Metric	Right	Large	High	.979	.977	
			Low	.946*	.975	
		Small	High	.971	.966	
			Low	.983	.968	
		Left	Large	High	.974	.986
				Low	.980	.980
	Small		High	.980	.986	
			Low	.979	.975	
	Topological	Right	Large	High	.948*	.967
				Low	.949*	.983
			Small	High	.962	.979
				Low	.988	.986
Left			Large	High	.947*	.970
				Low	.935*	.949*
		Small	High	.977	.981	
			Low	.979	.974	

\* $p < .05$

## Appendix I

i. ANOVA Table for Transformed Efficiency Scores for Block Effects (Block x Task x Hemisphere x Bin x Frequency)

Source	<i>df</i>	<i>F</i> Efficiency Score
Within subjects		
<i>Main Effects</i>		
Block (Bl)	1	726.852**
Bl within-group error	54	(0.005)
<i>Two-way Interactions</i>		
Bl X T	1	3.548
T within-group error	54	(0.006)
Bl x H	1	5.644*
H within-group error	54	(0.001)
Bl x B	1	26.095**
B within-group error	54	(0.001)

Bl x F	1	11.855*
F within-group		
error	54	(0.001)
<i>Three-way Interactions</i>		
Bl x T x H	1	0.430
T x H within-group		
error	54	(0.001)
Bl x T x B	1	4.171*
T x B within-group		
error	54	(0.001)
Bl x T x F	1	0.294
T x F within-group		
error	54	(0.001)
Bl x H x B	1	2.550
H x B within-group		
error	54	(0.001)
Bl x H x F	1	1.825
H x F within-group		
error	54	(0.001)
<i>Four-way Interactions</i>		
Bl x T x H x B	1	0.369
T x H x B within-group		
error	54	(0.001)

Bl x T x H x F	1	2.152
T x H x F within-group		
error	54	(0.001)
Bl x T x B x F	1	0.010
T x B x F within-group		
error	54	(0.001)
Bl x H x B x F	1	7.469*
H x B x F within-group		
error	54	(0.001)
<i>Five-way interaction</i>		
Bl x T x H x B x F	1	0.851
T x H x B x F within-group		
error	1	(0.001)

---

\* $p < .05$ ; \*\* $p < .001$

ii. Means and Standard Deviations for Each Variable and Each Block with Significant Between Block Differences Indicated.

Variable				Block 1	Block 2	
Task	Hemisphere	Bin	Frequency	M( <i>SD</i> )	M( <i>SD</i> )	
Metric	Right	Large	High	-.826(0.076)	-.774(0.072)*	
			Low	-.840(0.076)	-.792(0.077)*	
		Small	High	-.830(0.089)	-.791(0.083)*	
			Low	-.854 (0.088)	-.813(0.086)*	
		Left	Large	High	-.820(0.071)	-.778(0.071)*
				Low	-.845(0.078)	-.794(0.069)*
	Small		High	-.838(0.095)	-.796(0.075)*	
			Low	-.834(0.088)	-.800(0.087)*	
	Topological	Right	Large	High	-.639(0.068)	-.612(0.072)*
				Low	-.669(0.069)	-.634(0.078)*
			Small	High	-.666(0.077)	-.632(0.074)*
				Low	-.695(0.080)	-.660(0.077)*
Left			Large	High	-.634(0.067)	-.599(0.071)*
				Low	-.656(0.068)	-.629(0.083)*
		Small	High	-.661(0.073)	-.626(0.076)*	
			Low	-.688(0.077)	-.647(0.082)*	

\* $p < .002$

## Appendix J

i. ANOVA Table for Transformed Efficiency Scores for Sex effects, Block 1 (Sex x Task x Hemisphere x Bin x Frequency)

Source	<i>df</i>	<i>F</i> Efficiency Score
Between subjects		
<i>Main Effects</i>		
Sex (S)	1	0.591
S between-groups		
error	54	(0.062)
<i>Two-way Interactions</i>		
S x T	1	3.139
T within-group		
error	54	(0.010)
S x H	1	0.311
F within-group		
error	54	(0.001)
S x B	1	0.988
B within-group		
error	54	(0.002)
S x F	1	0.413

F within-group		
error	54	(0.001)
<i>Three-way Interactions</i>		
S x T x H	1	0.050
T x H within-group		
error	54	(0.001)
S x T x B	1	1.038
T x B within-group		
error	54	(0.001)
S x T x F	1	0.670
T x F within-group		
error	54	(0.001)
S x H x B	1	0.682
H x B within-group		
error	54	(0.001)
S x H x F	1	0.177
H x F within-group		
error	54	(0.001)
<i>Four-way Interactions</i>		
S x T x H x B	1	0.133
T x H x B within-group		
error	54	(0.001)
S x T x H x F	1	0.509

T x H x F within-group		
error	54	(0.001)
S x T x B x F	1	0.264
T x B x F within-group		
error	54	(0.001)
S x H x B x F	1	7.148*
H x B x F within-group		
error	54	(0.001)
<i>Five-way interaction</i>		
S x T x H x B x F	1	0.022
T x H x B x F within-group		
error	54	(0.001)

---

\* $p < .05$ ; \*\* $p < .001$

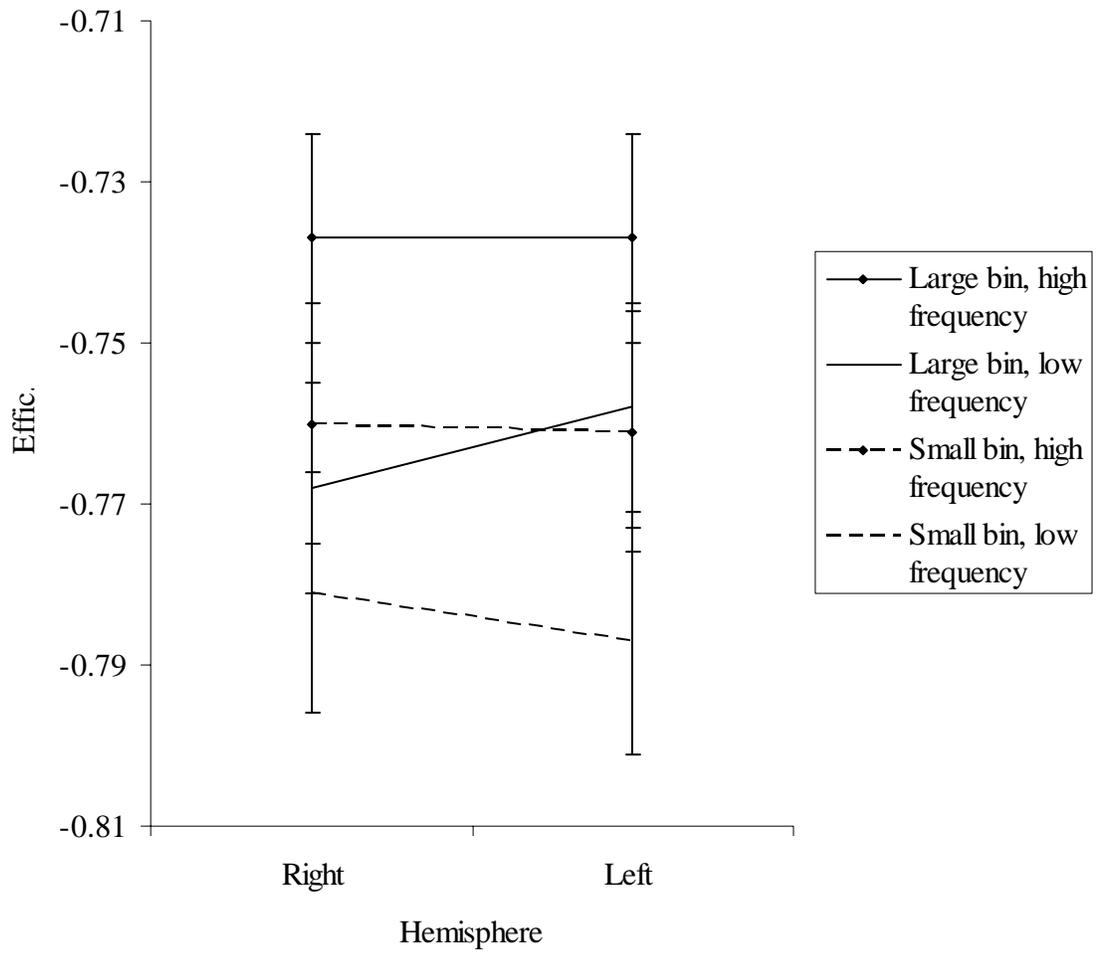


Figure Jii. Mean log transformed efficiency scores for male participants in block 1. No significant hemisphere x bin x frequency interaction emerged.

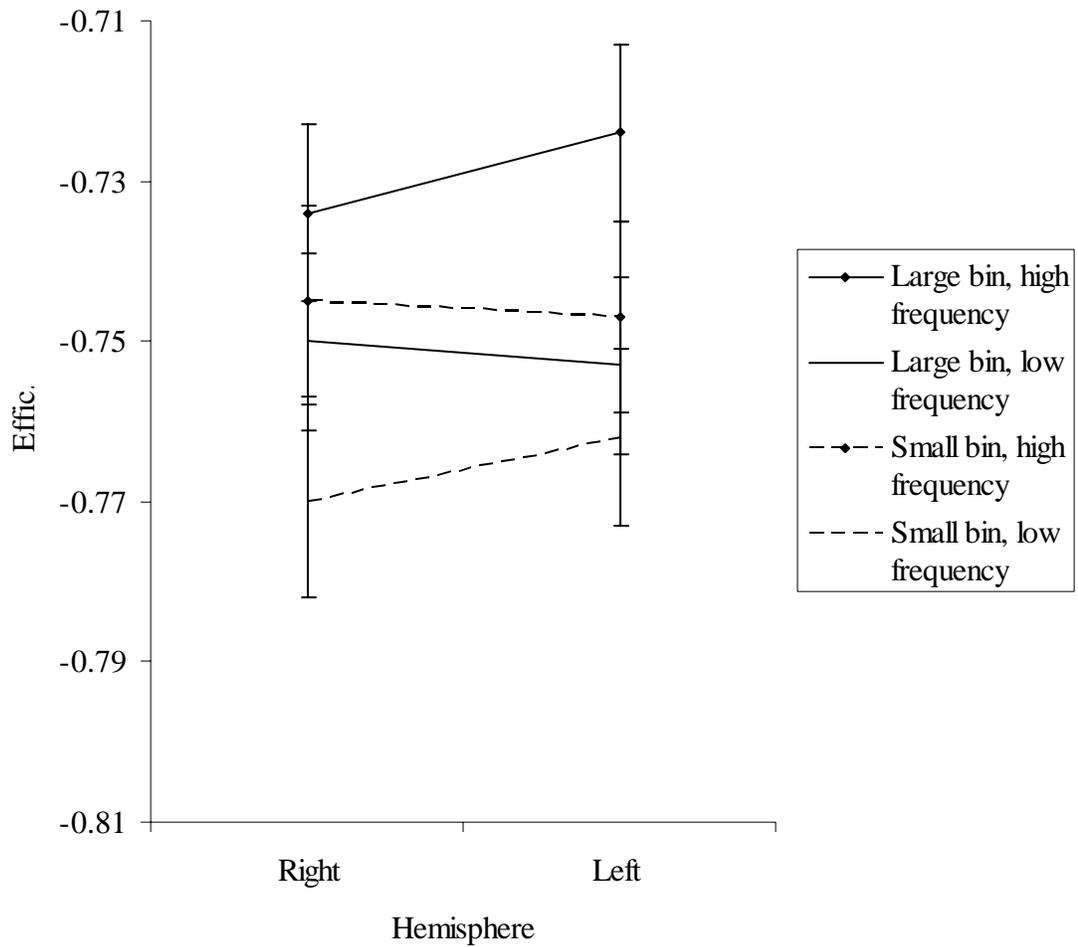


Figure Jiii. Mean log transformed efficiency scores for female participants in block 1 showing a hemisphere x bin x frequency interaction with hemispheric asymmetries evident under both high and low spatial frequency conditions. Under high spatial frequency conditions, female participants performed better with the left hemisphere than the right when bin size was large and better with the right hemisphere than the left when bin size was small. Under low spatial frequency conditions, female participants performed better with the left hemisphere than the right when bin size was small and better with the right hemisphere than the left when bin size was large.

Appendix K

i. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants,  
Hemisphere(Task Consistent) x Condition (Hemispherically Inconsistent)

Source	df	F
		Efficiency Score
Within subjects		
Hemisphere (task consistent)(Htc)	1	148.381**
Condition (hemispherically consistent)(Chi)	1	52.844**
Htc x Chi	1	19.842**
Htc x Chi within-group error	23	(0.001)

\*\* $p < .001$

ii. Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for Block 1, Male Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)

Pair	<i>df</i>	<i>t</i>	<i>p</i>
Left hemisphere (topological)			
Large bin, high frequency – Small bin, low frequency	23	10.386	<.001**
Right hemisphere (metric)			
Large bin, high frequency – Small bin, low frequency	25	2.491	.020*

\*  $p < .05$ ; \*\*  $p < .001$

iii. ANOVA Table of Transformed Efficiency Scores for Block 1, Male Participants, Task  
*x Hemisphere x Bin x Frequency*

Source	<i>df</i>	<i>F</i>
		Efficiency Score
Within subjects		
<i>Main Effects</i>		
Task (T)	1	181.672**
T within-group		
error	22	(0.013)
Hemisphere (H)	1	0.036
H within-group		
error	22	(0.001)
Bin Size (B)	1	23.252**
B within-group		
error	22	(0.001)
Frequency (F)	1	94.800**
F within-group		
Error	22	(0.001)

*Two-way Interactions*

T x H	1	0.815
T x H within-group		
error	22	(0.002)
T x B	1	17.783**
T x B within-group		
error	22	(0.002)
T x F	1	4.182*
T x F within-group		
error	22	(0.001)
H x B	1	2.296
H x B within-group		
error	22	(0.001)
H x F	1	0.130
H x F within-group		
error	22	(0.001)
B x F	1	1.789
B x F within-group		
error	22	(0.001)
<i>Three-way Interactions</i>		
T x H x B	1	0.050
T x H x B within-group		
error	22	(0.001)
T x H x F	1	0.349

T x H x F within-group		
error	22	(0.001)
T x B x F	1	0.048
T x B x F within-group		
error	22	(0.001)
H x B x F	1	1.785
H x B x F within-group		
error	22	(0.001)
<i>Four-way Interaction</i>		
T x H x B x F		
T x H x B x F within-group		
error	1	2.931

---

\*\* $p < .001$ ; \* $p < .05$

iv. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants,  
 Task x Hemisphere, Large Bin, High Frequency Conditions

Source	df	F
		Efficiency Score
Within subjects		
Task (T)	1	272.429**
Hemisphere (H)	1	0.000
T x H	1	0.074
T x H within-group		
error	23	(0.001)

\*\* $p < .001$

v. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Task x Hemisphere, Large Bin, Low Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	193.661**	
Hemisphere (H)	1	1.111	
T x H	1	2.244	
T x H within-group			
error	23	(0.001)	

\*\* $p < .001$

vi. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants,  
 Task x Hemisphere, Small Bin, High Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	122.874**	
Hemisphere (H)	1	0.093	
T x H	1	2.115	
T x H within-group			
Error	23	(0.001)	

\*\* $p < .001$

vii.. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants,  
 Task x Hemisphere, Small Bin, Low Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	86.533**	
Hemisphere (H)	1	1.296	
T x H	1	0.558	
T x H within-group			
Error	23	(0.001)	

\*\* $p < .001$

viii. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants,  
Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)

Source	df	F	
		Efficiency Score	
Within subjects			
Hemisphere (task consistent)(Htc)	1	214.915**	
Condition (Hemispherically consistent)(Chc)	1	0.015	
Htc x Chc	1	1.328	
Htc x Chc within-group error	23	(0.002)	

\*\* $p < .001$

ix. Means and Standard Deviations for Each Variable for Block 1, Male Participants.

---

Variable				
Task	Hemisphere	Bin	Frequency	M(SD)
Metric	Right	Large	High	-.815(0.094)
			Low	-.831(0.087)
		Small	High	-.822(0.099)
			Low	-.846 (0.094)
	Left	Large	High	-.813(0.081)
			Low	-.846(0.090)
		Small	High	-.820(0.098)
			Low	-.842(0.089)
Topological	Right	Large	High	-.640(0.086)
			Low	-.681(0.081)
		Small	High	-.676(0.100)
			Low	-.695(0.109)
	Left	Large	High	-.650(0.071)
			Low	-.670(0.068)
		Small	High	-.673(0.081)
			Low	-.700(0.104)

---

Appendix L

i. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
Hemisphere(Task Consistent) x Condition (Hemispherically Inconsistent)

Source	<i>df</i>	<i>F</i> Efficiency Score
Within subjects		
Hemisphere (task consistent)(Htc)	1	529.297**
Condition (hemispherically consistent)(Chi)	1	32.043**
Htc x Chi	1	6.696*
Htc x Chi within-group error	32	(0.001)

\*  $p < .05$ ; \*\* $p < .001$

ii. Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for Block 1, Female Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)

Pair	<i>df</i>	<i>t</i>	<i>p</i>
Left hemisphere (topological)			
Large bin, high frequency – Small bin, low frequency	34	8.102	<.001**
Right hemisphere (metric)			
Large bin, high frequency – Small bin, low frequency	33	2.362	.024*

\*  $p < .05$ ; \*\*  $p < .001$

iii. ANOVA Table of Transformed Efficiency Scores for Block 1, Female Participants,  
 Task x Hemisphere x Bin x Frequency

Source	df	<i>F</i>
		Efficiency Score
Within subjects		
<i>Main Effects</i>		
Task (T)	1	541.525**
T within-group		
error	32	(0.008)
Hemisphere (H)	1	1.320
H within-group		
error	32	(0.001)
Bin Size (B)	1	14.542*
B within-group		
error	32	(0.002)
Frequency (F)	1	35.422**
F within-group		
error	32	(0.002)
<i>Two-way Interactions</i>		

T x H	1	1.458
T x H within-group		
error	32	(0.001)
T x B	1	11.769*
T x B within-group		
error	32	(0.001)
T x F	1	1.766
T x F within-group		
error	32	(0.001)
H x B	1	0.018
H x B within-group		
error	32	(0.001)
H x F	1	0.450
H x F within-group		
error	32	(0.001)
B x F	1	0.145
B x F within-group		
error	32	(0.001)
<i>Three-way Interactions</i>		
T x H x B	1	0.881
T x H x B within-group		
error	32	(0.001)
T x H x F	1	0.160

T x H x F within-group		
error	32	(0.001)
T x B x F	1	0.294
T x B x F within-group		
error	32	(0.001)
H x B x F	1	6.826*
H x B x F within-group		
error	32	(0.001)
<i>Four-way Interaction</i>		
T x H x B x F	1	3.585 <sup>m</sup>
T x H x B x F within-group		
error	32	(0.001)

---

\* $p < .05$ ; \*\* $p < .001$ ; <sup>m</sup> = marginal

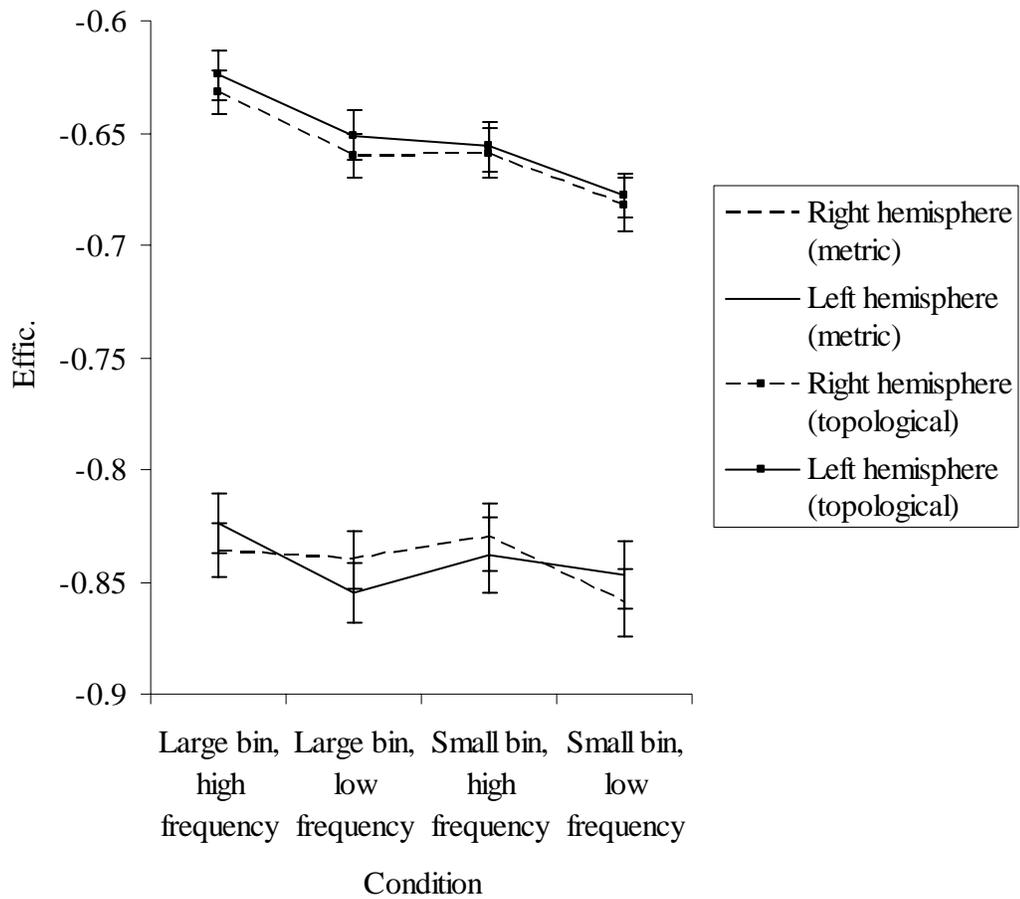


Figure Liv. Mean log transformed efficiency scores for female participants in block 1 for the 4-way (task x hemisphere x bin x frequency) showing a significant four-way interaction attributable to a performance decrement for the right hemisphere on the metric task under small bin, low frequency conditions. Effic. = Transformed efficiency scores.

v. ANOVA Table of Transformed Efficiency Scores for Block 1, Female Participants,  
 Topological task, Hemisphere x Bin x Frequency

Source	<i>df</i>	<i>F</i> Efficiency Score
<i>Within subjects</i>		
<i>Main Effects</i>		
Hemisphere (H)	1	5.097*
H within-group error	34	(0.001)
Bin Size (B)	1	4.515*
B within-group error	34	(0.001)
Frequency (F)	1	48.241**
F within-group error	34	(0.001)
<i>Two-way Interactions</i>		
H x B	1	0.666
H x B within-group error	34	(0.001)

H x F	1	0.013
H x F within-group		
error	34	(<0.001)
B x F	1	0.412
B x F within-group		
error	34	(0.001)
<i>Three-way Interactions</i>		
H x B x F	1	0.859
H x B x F within-group		
error	34	(0.001)

---

\* $p < .05$ ; \*\* $p < .001$

vi. ANOVA Table of Transformed Efficiency Scores for Block 1, Female Participants,  
Metric task, Hemisphere x Bin x Frequency

Source	<i>df</i>	<i>F</i> Efficiency Score
Within subjects		
<i>Main Effects</i>		
Hemisphere (H)	1	0.255
H within-group		
error	33	(0.001)
Bin Size (B)	1	1.202
B within-group		
error	33	(0.003)
Frequency (F)	1	12.156*
F within-group		
error	33	(0.002)
<i>Two-way Interactions</i>		
H x B	1	0.447
H x B within-group		
error	33	(0.001)
H x F	1	0.108

H x F within-group		
error	33	(0.001)
B x F	1	0.004
B x F within-group		
error	33	(0.002)
<i>Three-way Interactions</i>		
H x B x F	1	7.819
H x B x F within-group		
error	33	(0.002)

---

\* $p < .05$ ; \*\* $p < .001$

vii. ANOVA Table of Transformed Efficiency Scores for Block 1, Female Participants,  
Metric task, Left Hemisphere, Bin x Frequency

Source	df	<i>F</i>
		Efficiency Score
Within subjects		
<i>Main Effects</i>		
Bin Size (B)	1	0.260
B within-group		
error	33	(0.002)
Frequency (F)	1	7.951*
F within-group		
error	33	(0.002)
<i>Two-way Interactions</i>		
B x F	1	3.326
B x F within-group		
error	33	(0.002)

\* $p < .05$ ; \*\* $p < .001$

viii. ANOVA Table of Transformed Efficiency Scores for Block 1, Female Participants,  
Metric task, Right Hemisphere, Bin x Frequency

Source	<i>df</i>	<i>F</i>
		Efficiency Score
Within subjects		
<i>Main Effects</i>		
Bin Size (B)	1	1.454
B within-group		
error	33	(0.002)
Frequency (F)	1	5.501*
F within-group		
error	33	(0.002)
<i>Two-way Interactions</i>		
B x F	1	4.616*
B x F within-group		
error	33	(0.001)

\* $p < .05$ ; \*\* $p < .001$

ix. Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for Block 1, Female Participants, Metric Task, Right Hemisphere, Bin x Frequency

Pair		<i>df</i>	<i>t</i>	<i>p</i>
Bin	Frequency			
:Large	High			
Large	Low	34	0.266	.791
Large	High			
Small	High	33	-0.328	.745
Large	High			
Small	Low	33	2.362	.024
Large	Low			
Small	High	33	-0.612	.545
Large	Low			
Small	Low	33	2.294	.028
Small	High			
Small	Low	33	3.040	.005*

\*  $p < .01$

x. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
 Task x Hemisphere, Large Bin, High Frequency Conditions

Source	df	F
		Efficiency Score
Within subjects		
Task (T)	1	505.384**
Hemisphere (H)	1	2.963
T x H	1	0.146
T x H within-group		
error	32	(0.001)

\*\* $p < .001$

xi. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
 Task x Hemisphere, Large Bin, Low Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	468.857**	
Hemisphere (H)	1	0.192	
T x H	1	6.455*	
T x H within-group			
error	32	(0.001)	

\*  $p < .05$ ; \*\* $p < .001$

*xii. Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for Block 1, Female Participants, Task x Hemisphere, Large Bin, Low Frequency*

Pair	<i>df</i>	<i>t</i>	<i>p</i>
Topological			
Left hemisphere - Right hemisphere	34	-1.731	.092
Metric			
Left hemisphere - Right hemisphere	34	1.752	.089

xiii. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
 Task x Hemisphere, Small Bin, High Frequency Conditions

Source	df	F
		Efficiency Score
Within subjects		
Task (T)	1	310.140**
Hemisphere (H)	1	0.124
T x H	1	1.123
T x H within-group		
error	32	(0.001)

\*\* $p < .001$

xiv. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
 Task x Hemisphere, Small Bin, Low Frequency Conditions

Source	df	F
		Efficiency Score
Within subjects		
Task (T)	1	276.094**
Hemisphere (H)	1	3.058
T x H	1	0.569
T x H within-group		
error	32	(0.001)

\*\* $p < .001$

xv. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)

Source	df	F
		Efficiency Score
Within subjects		
Hemisphere (task consistent)(Htc)	1	370.702**
Condition (Hemispherically consistent)(Chc)	1	0.012
Htc x Chc	1	0.897
Htc x Chc within-group error	33	(0.001)

\*\* $p < .001$

xvi. Means and Standard Deviations for Each Variable for Block 1, Female

Participants.

---

Variable				
Task	Hemisphere	Bin	Frequency	M(SD)
Metric	Right	Large	High	-.830(0.071)
			Low	-.832(0.079)
		Small	High	-.823(0.088)
			Low	-.860 (0.084)
	Left	Large	High	-.815(0.080)
			Low	-.842(0.084)
		Small	High	-.842(0.099)
			Low	-.837(0.092)
Topological	Right	Large	High	-.632(0.060)
			Low	-.660(0.058)
		Small	High	-.659(0.061)
			Low	-.682(0.068)
	Left	Large	High	-.623(0.064)
			Low	-.646(0.067)
		Small	High	-.651(0.067)
			Low	-.678(0.061)

---

Appendix M

i. ANOVA Table for Transformed Efficiency Scores for Block 2, Sex x Task x

*Hemisphere x Bin x Frequency*

Source	<i>df</i>	<i>F</i> Efficiency Score
<u>Between subjects</u>		
Sex (S)	1	0.354
S between-group		
Error	55	(0.058)
Within subjects		
<i>Two-way Interactions</i>		
S x T	1	0.052
T within-group		
error	55	(0.013)
S x H	1	2.371
H within-group		
error	55	(0.001)
S x B	1	1.049

B within-group		
error	55	(0.002)
S x F	1	1.957
F within-group		
error	55	(0.001)
<i>Three-way Interactions</i>		
S x T x H	1	0.157
T x H within-group		
error	55	(0.001)
S x T x B	1	1.694
T x B within-group		
error	55	(0.001)
S x T x F	1	0.089
T x F within-group		
error	55	(0.001)
S x H x B	1	1.554
H x B within-group		
error	55	(0.001)
S x H x F	1	0.020
H x F within-group		
error	55	(0.001)
<i>Four-way Interactions</i>		
S x T x H x B	1	2.284

T x H x B within-group		
error	55	(0.001)
S x T x H x F	1	0.080
T x H x F within-group		
error	55	(0.001)
S x T x B x F	1	0.068
T x B x F within-group		
error	55	(0.001)
S x H x B x F	1	0.003
H x B x F within-group		
error	55	(0.001)
<i>Five-way interaction</i>		
S x T x H x B x F	1	4.844*
T x H x B x F within-group		
error	55	(0.001)

---

\*  $p < .05$ ; \*\*  $p < .001$

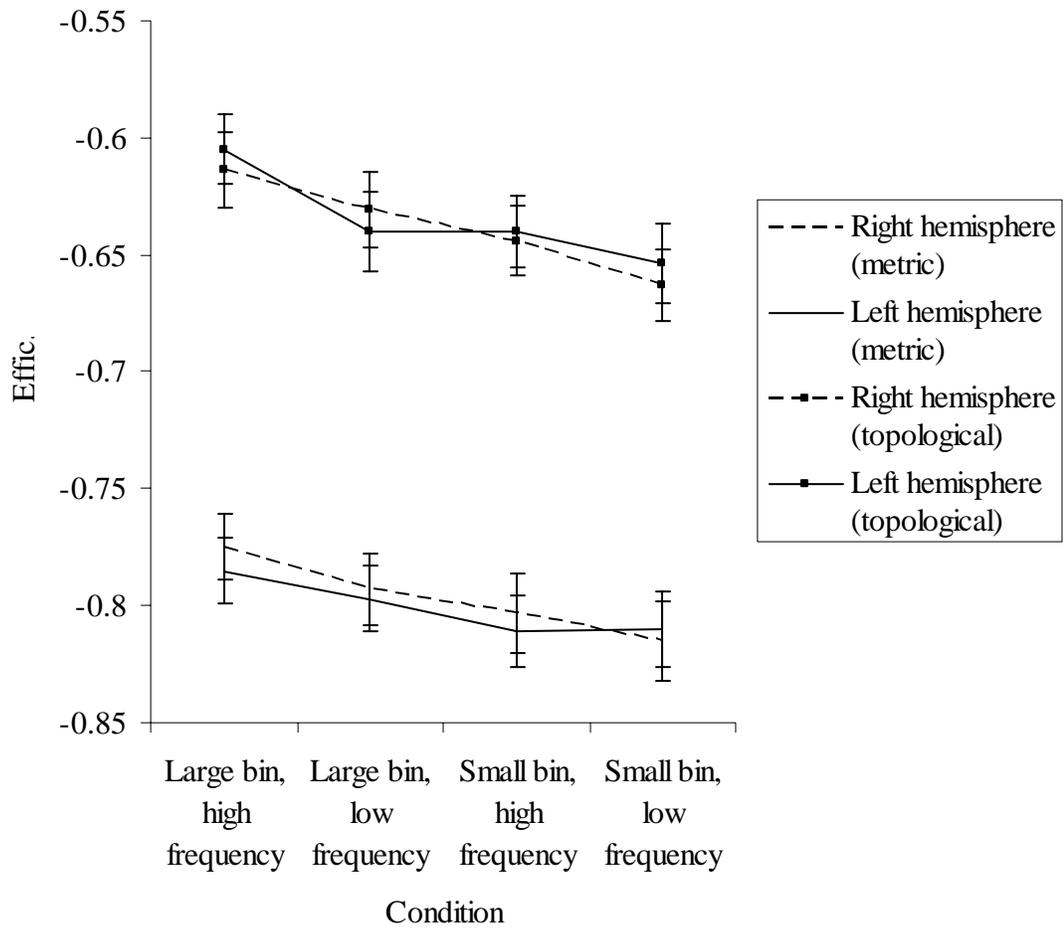


Figure Mii. Mean log transformed efficiency scores for male participants in block 2 for the 4-way (task x hemisphere x bin x frequency). Only main effects for task, bin and frequency emerged showing better performance on the topological task, under large bin conditions and under high frequency conditions. Effic. = Transformed efficiency scores.

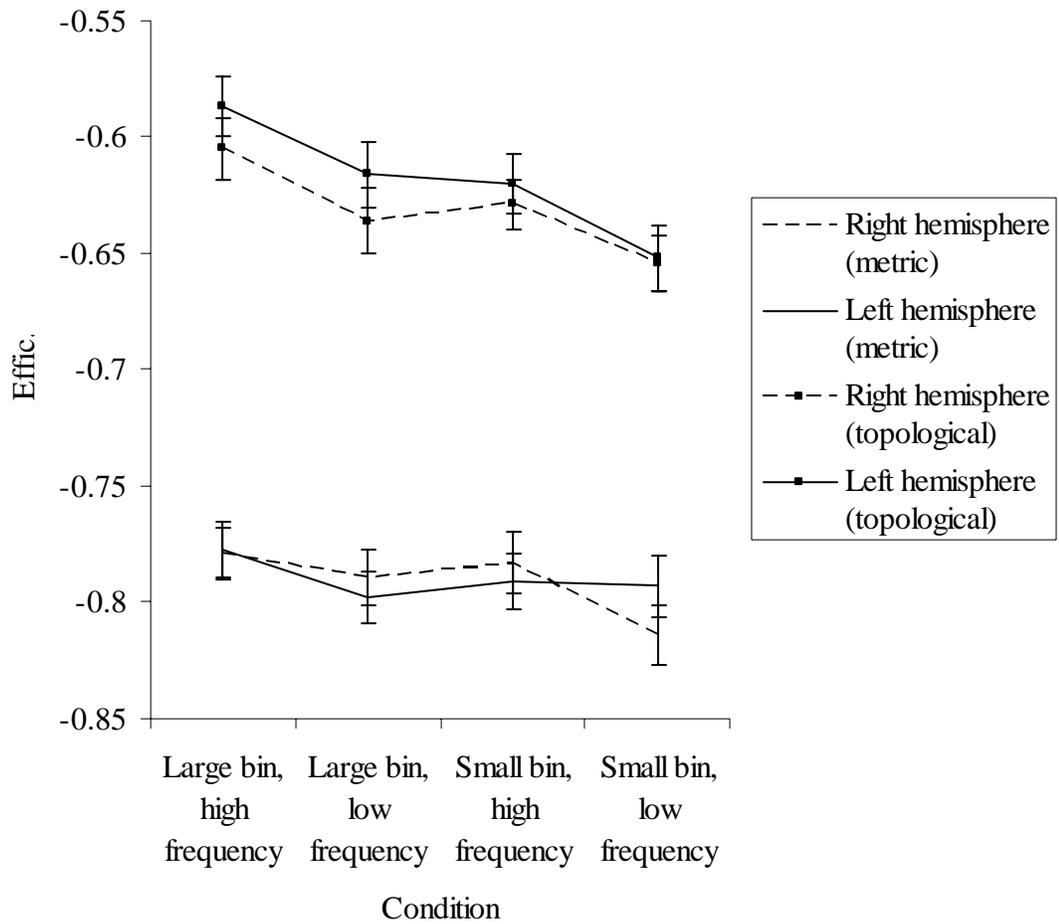


Figure Miii. Mean log transformed efficiency scores for female participants in block 2 for the 4-way (task x hemisphere x bin x frequency) analysis. Figure shows a significant four-way interaction. Effic. = Transformed efficiency scores.

Appendix N

i. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants,  
Hemisphere(Task Consistent) x Condition (Hemispherically Inconsistent)

		<i>F</i>
Source	<i>df</i>	Efficiency Score
Within subjects		
Hemisphere (task consistent)(Htc)	1	210.551**
Condition (hemispherically consistent)(Chi)	1	26.318**
Htc x Chi	1	0.525
Htc x Chi within-group error	23	(0.001)

\*\* $p < .001$

ii. ANOVA Table of Transformed Efficiency Scores for Block 2, Male Participants, Task  
*x Hemisphere x Bin x Frequency*

Source	<i>df</i>	<i>F</i>
		Efficiency Score
Within subjects		
<i>Main Effects</i>		
Task (T)	1	191.554**
T within-group		
error	21	(0.012)
Hemisphere (H)	1	0.021
H within-group		
error	21	(0.001)
Bin Size (B)	1	25.227**
B within-group		
error	21	(0.002)
Frequency (F)	1	20.991**
F within-group		
error	21	(0.001)

*Two-way Interactions*

T x H	1	0.702
T x H within-group		
error	21	(0.002)
T x B	1	0.567
T x B within-group		
error	21	(0.001)
T x F	1	2.914
T x F within-group		
error	21	(0.001)
H x B	1	1.187
H x B within-group		
error	21	(0.001)
H x F	1	0.055
H x F within-group		
error	21	(0.001)
B x F	1	2.722
B x F within-group		
error	21	(0.001)
<i>Three-way Interactions</i>		
T x H x B	1	0.002
T x H x B within-group		
error	21	(0.001)
T x H x F	1	1.222

T x H x F within-group		
error	21	(0.001)
T x B x F	1	0.009
T x B x F within-group		
error	21	(0.001)
H x B x F	1	1.302
H x B x F within-group		
error	21	(0.001)
<i>Four-way Interaction</i>		
T x H x B x F	1	0.400
T x H x B x F within-group		
error	21	(0.001)

---

\*\* $p < .001$

iii. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants,  
 Task x Hemisphere, Large Bin, High Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	212.502**	
Hemisphere (H)	1	0.065	
T x H	1	2.812	
T x H within-group			
error	22	(0.001)	

\*\* $p < .001$

iv. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants,  
 Task x Hemisphere, Large Bin, Low Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	184.569**	
Hemisphere (H)	1	0.948	
T x H	1	0.156	
T x H within-group			
error	21	(0.001)	

\*\* $p < .001$

v. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants, Task x Hemisphere, Small Bin, High Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	134.008**	
Hemisphere (H)	1	0.236	
T x H	1	0.905	
T x H within-group			
error	22	(0.001)	

\*\* $p < .001$

vi. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants,  
 Task x Hemisphere, Small Bin, Low Frequency Conditions

Source	<i>df</i>	<i>F</i>
		Efficiency Score
Within subjects		
Task (T)	1	108.314**
Hemisphere (H)	1	0.653
T x H	1	0.004
T x H within-group		
error	22	(0.001)

\*\* $p < .001$

vi. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants,  
Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)

Source	df	F
		Efficiency Score
Within subjects		
Hemisphere (task consistent)(Htc)	1	157.372**
Condition (Hemispherically consistent)(Chc)	1	0.082
Htc x Chc	1	0.799
Htc x Chc within-group error	23	(0.001)

\*\* $p < .001$

vii. Means and Standard Deviations for Each Variable for Block 2, Male Participants.

---

Variable				
Task	Hemisphere	Bin	Frequency	M(SD)
Metric	Right	Large	High	-.769(0.078)
			Low	-.792(0.095)
		Small	High	-.803(0.092)
			Low	-.809 (0.103)
	Left	Large	High	-.783(0.073)
			Low	-.791(0.078)
		Small	High	-.803(0.079)
			Low	-.818(0.089)
Topological	Right	Large	High	-.608(0.083)
			Low	-.630(0.076)
		Small	High	-.636(0.083)
			Low	-.670(0.073)
	Left	Large	High	-.597(0.088)
			Low	-.641(0.087)
		Small	High	-.631(0.082)
			Low	-.640(0.078)

---

Appendix O

i. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants,  
Hemisphere(Task Consistent) x Condition (Hemispherically Inconsistent)

Source	df	F
		Efficiency Score
Within subjects		
Hemisphere (task consistent)(Htc)	1	296.650**
Condition (hemispherically consistent)(Chi)	1	51.514**
Htc x Chc	1	7.576**
Htc x Chi within-group error	34	(0.001)

\*\* $p < .001$

ii. Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for  
 Block 2, Female Participants, Hemisphere (Task Consistent) x Condition  
 (Hemispherically Consistent)

Pair	<i>df</i>	<i>t</i>	<i>p</i>
Left hemisphere (topological)			
Large bin, high frequency – Small bin, low frequency	35	9.526	<.001**
Right hemisphere (metric)			
Large bin, high frequency – Small bin, low frequency	33	2.362	.024*

\*  $p < .05$ ; \*\*  $p < .001$

iii. ANOVA Table of Transformed Efficiency Scores for Block 2, Female Participants,  
 Task x Hemisphere x Bin x Frequency

Source	df	<i>F</i>
		Efficiency Score
Within subjects		
<i>Main Effects</i>		
Task (T)	1	300.978**
T within-group error	34	(0.013)
Hemisphere (H)	1	5.554*
H within-group error	34	(0.001)
Bin Size (B)	1	22.323*
B within-group error	34	(0.002)
Frequency (F)	1	53.871**
F within-group error	34	(0.001)
<i>Two-way Interactions</i>		
T x H	1	5.288*

T x H within-group		
error	34	(0.001)
T x B	1	9.545*
T x B within-group		
error	34	(0.001)
T x F	1	.5.824*
T x F within-group		
error	34	(0.001)
H x B	1	.324
H x B within-group		
error	34	(0.001)
H x F	1	.346
H x F within-group		
error	34	(0.001)
B x F	1	0.145
B x F within-group		
error	34	(0.001)
<i>Three-way Interactions</i>		
T x H x B	1	6.247*
T x H x B within-group		
error	34	(0.001)
T x H x F	1	0.982
T x H x F within-group		

error	34	(0.001)
T x B x F	1	0.090
T x B x F within-group		
error	34	(0.001)
H x B x F	1	3.554
H x B x F within-group		
error	34	(0.001)
<i>Four-way Interaction</i>		
T x H x B x F	1	8.275*
T x H x B x F within-group		
error	34	(0.001)

---

\* $p < .05$ ; \*\* $p < .001$

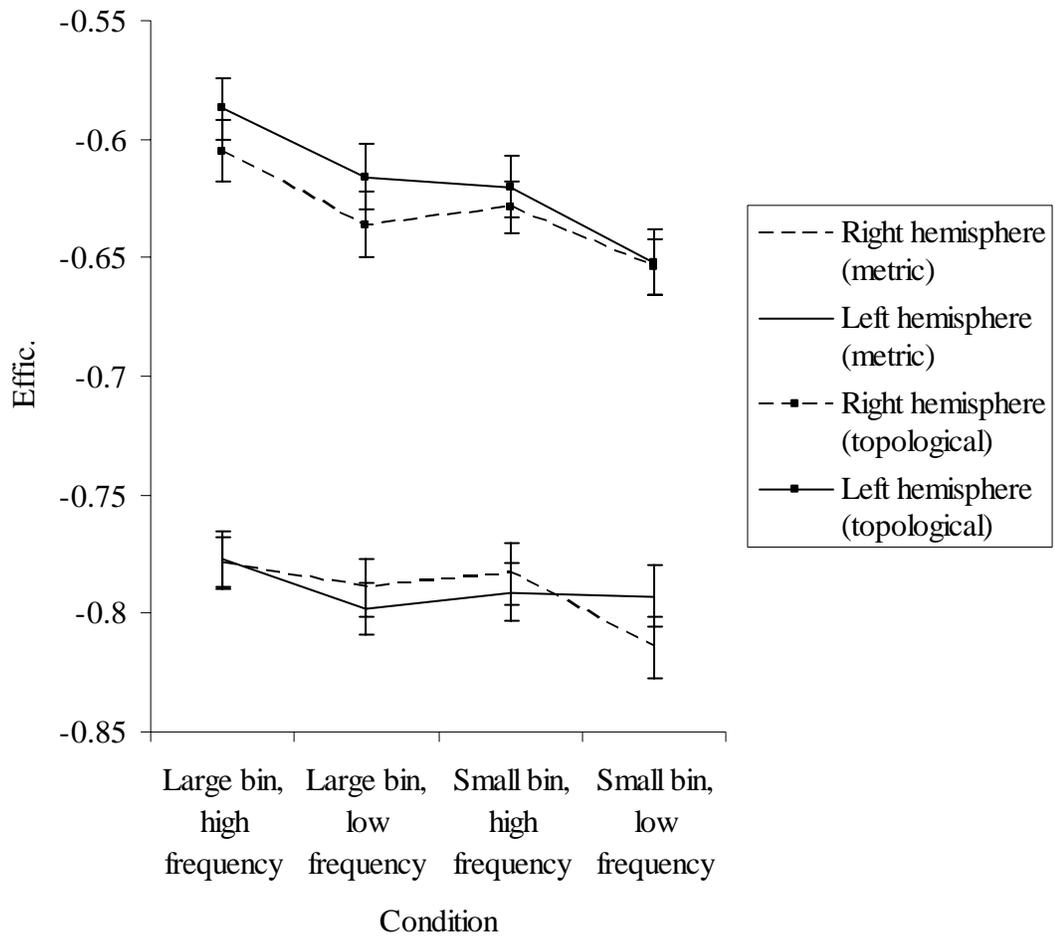


Figure Oiv. Log transform efficiency score means for female participants in block 2 showing a four-way (task x hemisphere x bin x frequency) interaction, Effic. = Transformed efficiency scores

v. ANOVA Table of Transformed Efficiency Scores for Block 2, Female Participants,  
 Topological task, Hemisphere x Bin x Frequency

Source	df	<i>F</i>
		Efficiency Score
Within subjects		
<i>Main Effects</i>		
Hemisphere (H)	1	12.000**
H within-group		
error	35	(0.001)
Bin Size (B)	1	59.340**
B within-group		
error	35	(0.001)
Frequency (F)	1	51.986**
F within-group		
error	35	(0.001)
<i>Two-way Interactions</i>		
H x B	1	4.834*
H x B within-group		
error	35	(0.001)
H x F	1	.427

H x F within-group		
error	35	(<0.001)
B x F	1	0.079
B x F within-group		
error	35	(0.001)
<i>Three-way Interactions</i>		
H x B x F	1	0.135
H x B x F within-group		
error	35	(<0.001)

---

\* $p < .05$ ; \*\* $p < .001$

vi. ANOVA Table of Transformed Efficiency Scores for Block 2, Female Participants,  
Metric task, Hemisphere x Bin x Frequency

Source	<i>df</i>	<i>F</i> Efficiency Score
Within subjects		
<i>Main Effects</i>		
Hemisphere (H)	1	0.159
H within-group		
error	34	(0.001)
Bin Size (B)	1	2.495
B within-group		
error	34	(0.002)
Frequency (F)	1	15.620*
F within-group		
error	34	(0.001)
<i>Two-way Interactions</i>		
H x B	1	2.043
H x B within-group		
error	34	(0.001)
H x F	1	0.765

H x F within-group		
error	34	(0.002)
B x F	1	0.014
B x F within-group		
error	34	(0.001)
<i>Three-way Interactions</i>		
H x B x F	1	8.129
H x B x F within-group		
error	34	(0.001)

---

\* $p < .05$

vii. ANOVA Table of Transformed Efficiency Scores for Block 2, Female Participants,  
Metric task, Left Hemisphere, Bin x Frequency

Source	<i>df</i>	<i>F</i>
		Efficiency Score
Within subjects		
<i>Main Effects</i>		
Bin Size (B)	1	0.499
B within-group		
error	34	(0.002)
Frequency (F)	1	4.422*
F within-group		
error	34	(0.001)
<i>Two-way Interactions</i>		
B x F	1	3.558 <sup>m</sup>
B x F within-group		
error	34	(0.001)

\* $p < .05$ ; <sup>m</sup> = marginal

viii. *Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for Block 2, Female Participants, Metric Task, Left Hemisphere, Bin x Frequency*

Pair		<i>df</i>	<i>t</i>	<i>p</i>
Bin	Frequency			
Large	High			
Large	Low	35	3.030	.005*
Large	High			
Small	High	34	1.150	.140
Large	High			
Small	Low	34	1.655	.107
Large	Low			
Small	High	34	-1.027	.312
Large	Low			
Small	Low	34	-0.687	.497
Small	High			
Small	Low	34	0.314	.756

\*  $p < .01$

ix. ANOVA Table of Transformed Efficiency Scores for Block 2, Female Participants,  
Metric task, Right Hemisphere, Bin x Frequency

Source	<i>df</i>	<i>F</i> Efficiency Score
<i>Within subjects</i>		
<i>Main Effects</i>		
Bin Size (B)	1	4.105
B within-group		
error	34	(0.002)
Frequency (F)	1	8.730*
F within-group		
error	34	(0.002)
<i>Two-way Interactions</i>		
B x F	1	3.997*
B x F within-group		
error	34	(0.001)

\*p.<.05

x. Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for  
 Block 2, Female Participants, Metric Task, Right Hemisphere, Bin x Frequency

Pair		<i>df</i>	<i>t</i>	<i>p</i>
Bin	Frequency			
:Large	High			
Large	Low	35	1.392	.173
Large	High			
Small	High	34	0.402	.690
Large	High			
Small	Low	34	3.249	.003*
Large	Low			
Small	High	34	-0.716	.479
Large	Low			
Small	Low	34	2.957	.006*
Small	High			
Small	Low	34	3.318	.002*

\*  $p < .01$

xi. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants,  
 Task x Hemisphere, Large Bin, High Frequency Conditions

Source	df	F
		Efficiency Score
Within subjects		
Task (T)	1	303.944**
Hemisphere (H)	1	4.855*
T x H	1	3.074
T x H within-group		
error	34	(0.001)

\*\* $p < .001$ ; \* $p < .05$

xii. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants,  
 Task x Hemisphere, Large Bin, Low Frequency Conditions

Source	<i>df</i>	<i>F</i>	
		Efficiency Score	
Within subjects			
Task (T)	1	203.320**	
Hemisphere (H)	1	2.150	
T x H	1	12.297*	
T x H within-group			
error	34	(0.001)	

\*  $p < .05$ ; \*\* $p < .001$

xiii. *Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for Block 2, Female Participants, Task x Hemisphere, Large Bin, Low Frequency*

Pair	<i>df</i>	<i>t</i>	<i>p</i>
Topological			
Left hemisphere -			
Right hemisphere	34	1.464	.152
Metric			
Left hemisphere -			
Right hemisphere	35	-3.473	.001**

\*\* $p \leq .001$

xiv. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants,  
 Task x Hemisphere, Small Bin, High Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	3289.896**	
Hemisphere (H)	1	0.963	
T x H	1	3.969*	
T x H within-group			
error	34	(0.001)	

\*  $p < .05$ ; \*\* $p < .001$

xv. *Significant Differences Between Relevant Pairs of Transformed Efficiency Scores for Block 2, Female Participants, Task x Hemisphere, Small Bin, High Frequency*

---

Pair	<i>df</i>	<i>t</i>	<i>p</i>
<hr/>			
Topological			
Left hemisphere -			
Right hemisphere	35	-1.590	.292
Metric			
Left hemisphere -			
Right hemisphere	34	1.070	.121

---

xvi. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants,  
 Task x Hemisphere, Small Bin, Low Frequency Conditions

Source	df	F
		Efficiency Score
Within subjects		
Task (T)	1	205.767**
Hemisphere (H)	1	3.946*
T x H	1	2.314
T x H within-group		
error	34	(0.001)

\*  $p < .05$ ; \*\* $p < .001$

xviii. ANOVA Table for Transformed Efficiency Scores for Block 2, Female

Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)

Source	df	F
		Efficiency Score
Within subjects		
Hemisphere (task consistent)(Htc)	1	220.522**
Condition (Hemispherically consistent)(Chc)	1	0.041
Htc x Chc	1	0.965
Htc x Chc within-group error	34	(0.001)

\*\* $p < .001$

xix. Means and Standard Deviations for Each Variable for Block 2, Female

Participants.

---

Variable				
Task	Hemisphere	Bin	Frequency	<i>M</i> ( <i>SD</i> )
Metric	Right	Large	High	-.775(0.071)
			Low	-.786(0.071)
		Small	High	-.783(0.076)
			Low	-.814 (0.077)
	Left	Large	High	-.772(0.074)
			Low	-.794(0.068)
		Small	High	-.791(0.073)
			Low	-.788(0.084)
Topological	Right	Large	High	-.604(0.078)
			Low	-.633(0.082)
		Small	High	-.627(0.068)
			Low	-.653(0.073)
	Left	Large	High	-.585(0.074)
			Low	-.610(0.088)
		Small	High	-.619(0.076)
			Low	-.645(0.088)

---

Appendix P

i. ANOVA Table for Mean Difference Scores For Block Effects for Block x Task x Hemisphere x Bin x Frequency x Exposure Duration (Greenhouse-Geisser Correction)

Source	<i>df</i>	<i>F</i> Efficiency Score
Within subjects		
<i>Main Effects</i>		
Block (Bl)	1	17.392*
Bl within-group		
Error	9	(2536.964)
<i>Two-way Interactions</i>		
Bl x T	1	0.532
Bl x T within-group		
error	9	(4156.723)
Bl x H	1	4.806
Bl x H within-group		
error	9	(14967.696)
Bl x B	1	14.310*
Bl x B within-group		

error	9	(1968.458)
Bl x F	1	27.044**
Bl x F within-group		
error	9	(3828.537)
Bl x E	1	22.984**
Bl x Exposure Duration (E)		
Within-group error	9	(526.437)
<i>Three-way Interactions</i>		
Bl x T x H	1	11.034*
Bl x T x H within-group		
error	9	(3042.810)
Bl x T x B	1	20.110**
Bl x T x B within-group		
error	9	(4670.675)
Bl x H x B	1	9.109*
Bl x H x B within-group		
error	9	(6125.453)
Bl x T x F	1	4.324
Bl x T x F within-group		
error	9	(1459.298)
Bl x H x F	1	0.176
Bl x H x F within-group		
error	9	(2968.497)

Bl x B x F	1	4.835
Bl x B x F within-group		
error	9	(2437.485)
Bl x T x E	1	0.162
Bl x T x E within-group		
error	9	(205.755)
Bl x B x E	1	1.793
Bl x B x E within-group		
error	9	(315.677)
Bl x H x E	1	3.247
Bl x H x E within-group		
error	9	(2424.853)
Bl x F x E	1	25.593**
Bl x F x E within-group		
error	9	(638.572)
<i>Four-way Interactions</i>		
Bl x T x H x B	1	1.235
Bl x T x H x B within-group		
error	9	(2611.160)
Bl x T x H x F	1	27.851**
Bl x T x H x F within-group		
error	9	(4849.445)
Bl x T x B x F	1	36.080**

Bl x T x B x F within-group		
error	9	(2906.945)
Bl x H x B x F	1	14.059*
Bl x H x B x F within-group		
error	9	(12232.801)
Bl x T x H x E	1	75.337**
Bl x T x H x E within-group		
error	9	(178.004)
Bl x T x B x E	1	155.354**
Bl x T x B x E within-group		
error	9	(73.882)
Bl x H x B x E	1	57.313
Bl x H x B x E within-group		
error	9	(299.844)
Bl x T x F x E	1	0.407
Bl x T x F x E within-group		
error	9	(230.586)
Bl x H x F x E	1	0.279
Bl x H x F x E within-group		
error	9	(191.960)
Bl x B x F x E	1	0.064
Bl x B x F x E within-group		
error	9	(304.781)

*Five-way interaction*

Bl x T x H x B x F	1	0.455
Bl x T x H x B x F within-group		
error	9	(2854.843)
Bl x T x H x B x E	1	0.090
Bl x T x H x B x E within-group		
error	9	(81.246)
Bl x T x H x F x E	1	112.173**
Bl x T x H x B x E within-group		
error	9	(127.672)
Bl x T x B x F x E	1	78.859**
Bl x T x B x F x E within-group		
error	9	(133.173)
Bl x H x B x F x E	1	125.792**
Bl x H x B x F x E within-group		
error	9	(71.311)

---

\*  $p < .05$ ; \*\*  $p < .001$

ii. Significant Differences Between Test Value (93.8) and Distance of Saccadic Movement (Pixels) for Each Block

Variable	<i>df</i>	<i>t</i>	<i>p</i>
Block 1			
Rightward 100 ms	11	-10.938	< .001
Rightward 117 ms	11	-4.006	= .002
Rightward 150 ms	11	2.576	= .026
Leftward 100 ms	11	9.294	< .001
Leftward 117 ms	11	5.155	< .001
Leftward 150 ms	11	0.145	NS
Block 2			
Rightward 100 ms	11	-9.928	< .001
Rightward 117 ms	11	-4.334	= .001
Rightward 150 ms	11	1.629	NS
Leftward 100 ms	11	6.879	< .001
Leftward 117 ms	11	2.973	= .013
Leftward 150 ms	11	-3.691	= .004

NS = non-significant

iii. Means for Distance of Saccadic Movement (pixels) for Each Block

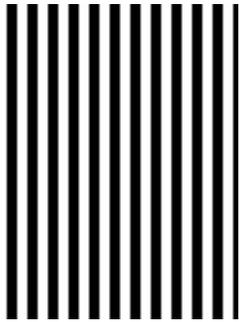
---

Variable	Block 1	Block 2
	<i>M(SD)</i>	<i>M(SD)</i>
Rightward 100 ms	39.1(17.3)	42.2(18.0)
Rightward 117 ms	64.3(25.5)	65.2(22.9)
Rightward 150 ms	121.8(37.7)	107.2(28.6)
Leftward 100 ms	-32.8(22.7)	-40.5(26.9)
Leftward 117 ms	-53.4(27.2)	-67.8(30.3)
Leftward 150 ms	-92.5(30.8)	-127.3(31.4)

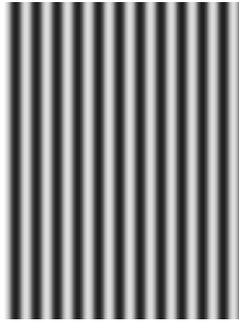
---

## Appendix Q

### i. High and Low Spatial Frequency Masks Used for Experiment 3



High spatial frequency



Low spatial frequency

Appendix R

i. Mean Reaction Time (Standard Deviation) and Accuracy (Standard Deviation) Data for All Variables ( $n = 60$ ).

Variable				RT( <u>SD</u> )	Acc.( <u>SD</u> )
Task	Hemisphere	Bin	Frequency		
			Block 1		
Metric	Right	Large	High	595(148)	.85(0.07)
			Low	595(146)	.84(0.07)
		Small	High	606(160)	.87(0.07)
			Low	615(172)	.83(0.10)
	Left	Large	High	584(136)	.85(0.08)
			Low	605(177)	.83(0.07)
		Small	High	609(162)	.84(0.08)
			Low	606(146)	.84(0.09)
Topological	Right	Large	High	412(89)	.98(0.04)
			Low	432(91)	.96(0.05)
		Small	High	463(127)	.96(0.07)
			Low	468(123)	.93(0.09)
	Left	Large	High	412(94)	.98(0.04)
			Low	422(92)	.96(0.06)
		Small	High	466(136)	.94(0.09)

			Low	471(134)	.92(0.09)
<hr/>					
			Block 2		
Metric	Right	Large	High	514(117)	.88(0.07)
			Low	517(112)	.85(0.09)
		Small	High	526(137)	.87(0.08)
			Low	522(124)	.85(0.09)
	Left	Large	High	512(121)	.87(0.08)
			Low	522(127)	.85(0.08)
		Small	High	520(125)	.85(0.08)
			Low	525(127)	.87(0.08)
Topological	Right	Large	High	374(82)	.98(0.03)
			Low	391(83)	.97(0.04)
		Small	High	415(105)	.97(0.05)
			Low	418(96)	.95(0.05)
	Left	Large	High	370(80)	.99(0.02)
			Low	381(87)	.96(0.04)
		Small	High	406(102)	.97(0.05)
			Low	422(116)	.94(0.06)

Note. RT = Reaction time. SD = Standard deviation. Acc. = Percent correct

## Appendix S

### i. Shapiro-Wilks Statistics for All Variables for Exposure Duration = 100 ms (df = 18)

Variable				Block 1	Block 2	
Task	Hemisphere	Bin	Frequency			
Metric	Right	Large	High	.989	.879*	
			Low	.968	.980	
		Small	High	.982	.895*	
			Low	.976	.980	
		Left	Large	High	.978	.964
				Low	.955	.971
	Small		High	.989	.964	
			Low	.960	.967	
	Topological	Right	Large	High	.978	.958
				Low	.982	.938
			Small	High	.975	.969
				Low	.952	.967
Left			Large	High	.926	.933
				Low	.957	.928
		Small	High	.954	.979	
			Low	.958	.922	

\* $p < .05$

ii. Shapiro-Wilks Statistics for All Variables for Exposure Duration = 150 ms ( $df = 26$ )

Variable				Block 1	Block 2
Task	Hemisphere	Bin	Frequency		
Metric	Right	Large	High	.960	.958
			Low	.928	.955
		Small	High	.969	.938
			Low	.967	.979
	Left	Large	High	.970	.979
			Low	.973	.971
		Small	High	.957	.961
			Low	.940	.958
Topological	Right	Large	High	.955	.970
			Low	.929	.976
		Small	High	.954	.975
			Low	.982	.990
	Left	Large	High	.916	.974*
			Low	.954	.970
		Small	High	.976	.994
			Low	.960	.969

\* $p < .05$

## Appendix T

i. ANOVA Table of Transformed Efficiency Scores for 5 Within (Block, Task, Hemisphere, Bin, Frequency) and 2 Between (Exposure Duration, Sex) for Block, Exposure Duration and Sex Effects

Source	df	F
Efficiency Score		
<b>Between Subjects</b>		
Exposure Duration (E)	1	0.012
E between-groups		
error	1	(0.001)
Sex(S)	1	0.383
S between-groups		
error	1	(0.044)
E x S	1	1.221
E x S within-group		
error	40	(0.116)
<i>Interactions with Block</i>		
E x Bl	1	3.228
S x Bl	1	(0.762)

E x S x Bl	1	0.236
Bl within-group		
error	40	(0.010)
<i>Interactions with Task</i>		
E x T	1	0.080
S x T	1	0.244
E x S x T	1	2.449
T within-groups		
error	40	(0.017)
<i>Interactions with Hemisphere</i>		
E x H	1	0.189
S x H	1	0.486
E x S x H	1	0.203
H within-group		
error	40	(0.002)
<i>Interactions with Bin</i>		
E x B	1	6.232*
S x B	1	0.379
E x S x B	1	1.478
B within-group		
error	40	(0.005)
<i>Interactions with Frequency</i>		
E x F	1	2.299

S x F	1	1.025
E x S x F	1	0.265
F within-group		
error	40	(0.001)

*Interactions with Block and Task*

E x Bl x T	1	0.000
S x Bl x T	1	4.697*
E x S x Bl x T	1	2.179
Bl x T within-group		
error	40	(0.006)

*Interactions with Block and Hemisphere*

E x Bl x H	1	0.118
S x Bl x H	1	0.944
E x S x Bl x H	1	0.101
Bl x H within-group		
error	40	(0.001)

*Interactions with Block and Bin Size*

E x Bl x B	1	6.827*
S x Bl x B	1	2.331
E x S x Bl x B	1	0.044
Bl x B within-group		
error	40	(0.001)

*Interactions with Block and Frequency*

E x Bl x F	1	2.253
------------	---	-------

S x Bl x F	1	1.354
E x S x Bl x F	1	1.155
Bl x F within-group		
error	40	(0.001)

*Interactions with Task and Hemisphere*

E x T x H	1	0.192
S x T x H	1	1.492
E x S x T x H	1	1.297
T x H within-group		
error	40	(0.001)

*Interactions with Task and Bin Size*

E x T x B	1	6.787*
S x T x B	1	0.487
E x S x T x B	1	0.062
T x B within-group		
error	40	(0.002)

*Interactions with Task and Frequency*

E x T x F	1	0.289
S x T x F	1	0.231
E x S x T x F	1	0.830
T x F within-group		
error	40	(0.001)

*Interactions with Hemisphere and Bin Size*

E x H x B	1	0.220
S x H x B	1	0.571
E x S x H x B	1	0.875
H x B within-group		
error	40	(0.002)

*Interactions with Hemisphere and Frequency*

E x H x F	1	1.654
S x H x F	1	0.461
E x S x H x F	1	0.085
H x F within-group		
Error	40	(0.001)

*Interactions with Bin Size and Frequency*

E x B x F	1	0.492
S x B x F	1	1.292
E x S x B x F	1	0.019
B x F within-group		
error	40	(0.001)

*Interactions with Block, Task and Hemisphere*

E x Bl x T x H	1	0.345
S x Bl x T x H	1	2.820
E x S x Bl x T x H	1	5.374*
Bl x T x H within-group		
error	40	(0.001)

*Interactions with Block, Task and Bin Size*

E x Bl x T x B	1	0.017
S x Bl x T x B	1	1.624
E x S x Bl x T x B	1	0.005
Bl x T x B within-group		
error	40	(0.002)

*Interactions with Block, Task and Frequency*

E x Bl x T x F	1	0.649
S x Bl x T x F	1	0.802
E x S x Bl x T x F	1	0.202
Bl x T x F within-group		
error	40	(0.001)

*Interactions with Block, Hemisphere and Bin Size*

E x Bl x H x B	1	5.036*
S x Bl x H x B	1	0.355
E x S x Bl x H x B	1	2.165
Bl x H x B within-group		
error	40	(0.001)

*Interactions with Block, Hemisphere and Frequency*

E x Bl x H x F	1	5.131*
S x Bl x H x F	1	0.036
E x S x Bl x H x F	1	2.257
Bl x H x F within-group		

error	40	(0.001)
-------	----	---------

*Interactions with Block, Bin Size and Frequency*

E x Bl x B x F	1	0.072
----------------	---	-------

S x Bl x B x F	1	0.137
----------------	---	-------

E x S x Bl x B x F	1	2.899
--------------------	---	-------

Bl x B x F within-group

error	40	(0.001)
-------	----	---------

*Interactions with Task, Hemisphere and Bin Size*

E x T x H x B	1	3.244
---------------	---	-------

S x T x H x B	1	5.236*
---------------	---	--------

E x S x T x H x B	1	2.385
-------------------	---	-------

T x H x B within-group

error	40	(0.001)
-------	----	---------

*Interactions with Task, Hemisphere and Frequency*

E x T x H x F	1	0.096
---------------	---	-------

S x T x H x F	1	0.000
---------------	---	-------

E x S x T x H x F	1	0.967
-------------------	---	-------

T x H x F within-group

error	40	(0.001)
-------	----	---------

*Interactions with Task, Bin Size and Frequency*

E x T x B x F	1	0.014
---------------	---	-------

S x T x B x F	1	0.124
---------------	---	-------

E x S x T x B x F	1	0.086
-------------------	---	-------

T x B x F within-group		
error	40	(0.001)

*Interactions with Hemisphere, Bin Size and Frequency*

E x H x B x F	1	0.000
S x H x B x F	1	1.122
E x S x H x B x F	1	0.000

H x B x F within-group

error	40	(0.001)
-------	----	---------

*Interactions with Block, Task, Hemisphere and Bin Size*

E x Bl x T x H x B	1	0.411
S x Bl x T x H x B	1	1.937
E x S x Bl x T x H x B	1	0.849

Bl x T x H x B within-group

error	40	(0.001)
-------	----	---------

*Interactions with Block, Task, Hemisphere and Frequency*

E x Bl x T x H x F	1	0.005
S x Bl x T x H x F	1	0.015
E x S x Bl x T x H x F	1	0.533

Bl x T x H x F within-group

error	40	(0.001)
-------	----	---------

*Interactions with Block, Task, Bin Size and Frequency*

E x Bl x T x B x F	1	1.636
S x Bl x T x B x F	1	4.016*

E x S x Bl x T x B x F	1	0.100
Bl x T x B x F within-group		
error	40	(0.001)
<i>Interactions with Block, Hemisphere, Bin Size and Frequency</i>		
E x Bl x H x B x F	1	1.005
S x Bl x H x B x F	1	0.002
E x S x Bl x H x B x F	1	2.255
Bl x H x B x F within-group		
error	40	(0.001)
<i>Interactions with Task, Hemisphere, Bin Size and Frequency</i>		
E x T x H x B x F	1	0.495
S x T x H x B x F	1	1.289
E x S x T x H x B x F	1	0.347
T x H x B x F within-group		
error	40	(0.001)
<i>Interactions with Block, Task, Hemisphere, Bin Size and Frequency</i>		
E x Bl x T x H x B x F	1	0.175
S x Bl x T x H x B x F	1	0.002
E x S x Bl x T x H x B x F	1	1.931
Bl x T x H x B x F within-group		
error	40	(0.001)

---

Within subjects

*Main Effects*

Block (Bl)	1	83.156**
Task (T)	1	589.517**
Hemisphere (H)	1	0.001
Bin Size (B)	1	42.295**
Frequency (F)	1	94.124**

*Two-way Interactions*

Bl x T	1	3.079
Bl x H	1	0.137
Bl x F	1	0.023

*Three-way Interactions*

Bl x T x H	1	0.135
Bl x T x B	1	3.704
Bl x H x B	1	0.337
Bl x T x F	1	4.197*
Bl x H x F	1	2.729
Bl x B x F	1	1.645

*Four-way Interactions*

Bl x T x H x B	1	0.098
Bl x T x H x F	1	1.880
Bl x T x B x F	1	2.136
Bl x H x B x F	1	0.559

*Five-way Interaction*

Bl x T x H x B x F

1

0.597

---

\*\* $p < .001$ ; \* $p < .05$

ii. Means and Standard Deviations for Each Variable and Each Block With Significant  
Between Block Differences Indicated.

Variable				Block 1	Block 2
Task	Hemisphere	Bin	Frequency	M( <i>SD</i> )	M( <i>SD</i> )
Metric	Right	Large	High	-.842(.101)	-.771(0.084)*
			Low	-.852(.103)	-.784(0.082)*
		Small	High	-.841(.108)	-.775(0.090)*
			Low	-.867 (.122)	-.788(0.105)*
	Left	Large	High	-.834(.092)	-.769(0.076)*
			Low	-.852(.086)	-.784(0.078)*
		Small	High	-.862(.113)	-.790(0.094)*
			Low	-.870(.122)	-.788(0.105)*
Topological	Right	Large	High	-.628(.085)	-.581(0.090)*
			Low	-.660(.085)	-.610(0.087)*
		Small	High	-.681(.099)	-.634(0.092)*
			Low	-.701(.100)	-.649(0.088)*
	Left	Large	High	-.629(.090)	-.575(0.085)*
			Low	-.653(.092)	-.605(0.093)*
		Small	High	-.690(.130)	-.610(0.099)*
			Low	-.690(.098)	-.641(0.108)*

\* $p < .002$

Appendix U

i. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants,  
Hemisphere (Task Consistent) x Condition (Hemispherically Inconsistent)

Source	df	F	
		Efficiency Score	
Between Subjects			
Exposure Duration (E)	1	1476.234**	
E x Htc	1	0.033	
E x Chi	1	0.874	
E x Htc x Chi	1	0.003	
Htc x Chi within-group			
error	20	(0.038)	
Within subjects			
Hemisphere (task consistent)(Htc)	1	139.895**	
Condition (hemispherically inconsistent)(Chi)	1	23.318**	
Htc x Chi	1	2.689	
Htc x Chi within-group			

error	20	(0.002)
-------	----	---------

---

\*\* $p < .001$

ii. ANOVA Table of Transformed Efficiency Scores for Block 1, Male Participants,  
 Exposure Duration x Task x Hemisphere x Bin x Frequency

Source	df	F
		Efficiency Score
Between Subjects		
<i>Main Effects</i>		
Exposure Duration (E)	1	1476.234**
E between-groups		
error	18	(0.122)
<i>Two-way Interactions</i>		
E x T	1	1.103
T within-group		
error	18	(0.010)
E x H	1	0.037
H within-group		
error	18	(0.002)
E x B	1	3.252
B within-group		
error	18	(0.004)

E x F	1	1.454
F within-group		
error	18	(0.002)
<i>Three-way Interactions</i>		
E x T x H	1	1.809
T x H within-group		
error	18	(0.001)
E x T x B	1	0.420
T x B within-group		
error	18	(0.002)
E x H x B	1	1.121
H x B within-group		
error	18	(0.001)
E x T x F	1	0.022
T x F within-group		
error	18	(0.002)
E x H x F	1	0.533
H x F within-group		
error	18	(0.001)
E x B x F	1	1.338
B x F within-group		
error	18	(0.001)

*Four-way Interactions*

E x T x H x B	1	1.497
T x H x B within-group		
error	18	(0.001)
E x T x H x F	1	0.020
T x H x F within-group		
error	18	(0.002)
E x T x B x F	1	0.273
T x B x F within-group		
error	18	(0.001)
E x H x B x F	1	1.433
H x B x F within-group		
error	18	(0.002)
<i>Five-way Interaction</i>		
E x T x H x B x F	1	0.077
T x H x B x F within-group		
error	18	(0.002)

---

Within subjects

*Main Effects*

Task (T)	1	257.458**
Hemisphere (H)	1	0.330
Bin Size (B)	1	22.155**
Frequency (F)	1	14.236**

*Two-way Interactions*

T x H	1	1.356
T x B	1	7.915*
T x F	1	0.006
H x B	1	2.356
H x F	1	3.294
B x F	1	0.950
<i>Three-way Interactions</i>		
T x H x B	1	1.374
T x H x F	1	0.325
T x B x F	1	0.989
H x B x F	1	0.295
<i>Four-way Interaction</i>		
T x H x B x F	1	1.034

---

\*\* $p < .001$ ; \* $p < .05$

iii. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants,  
 Task x Hemisphere, Large Bin, High Frequency Conditions

Source	df	<i>F</i>
		Efficiency Score
Between Subjects		
Exposure Duration (E)	1	0.061
E between-groups		
Error	20	(0.028)
E x T	1	0.850
T within-group		
Error	20	(0.005)
E x H	1	0.022
H within-group		
Error	20	(0.001)
E x T x H	1	0.045
T x H within-group		
Error	20	(0.001)
Within subjects		
Task (T)	1	164.878**
Hemisphere (H)	1	0.070

T x H

1

1.170

---

\*\* $p < .001$

*iv. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants,  
Task x Hemisphere, Large Bin, Low Frequency Conditions*

Source	<i>df</i>	<i>F</i>
		Efficiency Score
<u>Between Subjects</u>		
Exposure Duration (E)	1	0.001
E between-groups		
Error	20	(0.021)
E x T	1	0.299
T within-group		
Error	20	(0.004)
E x H	1	0.862
H within-group		
Error	20	(0.003)
E x T x H	1	0.092
T x H within-group		
Error	20	(0.001)
<u>Within subjects</u>		
Task (T)	1	162.524**

Hemisphere (H)	1	0.555
T x H	1	0.031

---

**\*\*** $p < .001$

v. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants,  
 Task x Hemisphere, Small Bin, High Frequency Conditions

Source	df	<i>F</i>
		Efficiency Score
Between Subjects		
Exposure Duration (E)	1	1.664
E between-groups		
error	21	(0.040)
E x T	1	1.509
T within-group		
error	21	(0.003)
E x H	1	0.173
H within-group		
error	21	(0.001)
E x T x H	1	0.339
T x H within-group		
error	21	(0.001)
<u>Within subjects</u>		
Task (T)	1	170.493

Hemisphere (H)	1	4.825
T x H	1	1.262

---

**\*\* $p < .001$**

vi. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants,  
 Task x Hemisphere, Small Bin, Low Frequency Conditions

Source	df	<i>F</i>
		Efficiency Score
Between Subjects		
Exposure Duration (E)	1	0.547
E between-groups		
error	19	(0.033)
E x T	1	0.215
T within-group		
error	19	(0.004)
E x H	1	2.357
H within-group		
error	19	(0.002)
E x T x H	1	1.307
T x H within-group		
error	19	(0.003)

Within subjects

Task (T)	1	133.782**
Hemisphere (H)	1	0.227
T x H	1	1.211

---

\*\* $p < .001$

viii. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants,  
Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)

Source	df	<i>F</i>
		Efficiency Score
Between Subjects		
Exposure Duration (E)	1	0.084
E between-group		
error	21	(0.034)
E x Htc	1	0.439
Htc within-group		
error	21	(0.005)
E x Chc	1	3.386
Chc within-group		
error	21	(0.003)
E x Htc x Chc	1	0.090
Htc x Chc within-group		
error	21	(0.002)

Within subjects

Hemisphere (task consistent)(Htc)	1	122.201**
Condition (Hemispherically consistent)(Chc)	1	0.304
Htc x Chc	1	9.139*

---

\*  $p < .05$ ; \*\* $p < .001$

ix. Means and Standard Deviations for Each Variable for Block 1, Male Participants for the 150 and 100 ms Exposure Duration Groups

Variable				100 ms	150 ms	
Task	Hemisphere	Bin	Frequency	<i>M</i> ( <i>SD</i> )	<i>M</i> ( <i>SD</i> )	
Metric	Right	Large	High	-0.846(0.121)	-0.802(0.104)	
			Low	-.0846(0.108)	-0.827(0.105)	
		Small	High	-0.853(0.133)	-0.793(0.091)	
			Low	-0.878 (0.149)	-0.827(0.109)	
		Left	Large	High	-0.820(0.071)	-0.778(0.071)
				Low	-0.839(0.102)	-0.825(0.100)
	Small		High	-0.863(0.120)	-0.815(0.116)	
			Low	-0.872(0.096)	-.0853(0.074)	
	Topological	Right	Large	High	-0.619(0.093)	-0.605(0.091)
				Low	-0.661(0.085)	-0.640(0.075)
			Small	High	-0.705(0.102)	-0.642(0.093)
				Low	-0.707(0.093)	-0.658(0.111)
Left			Large	High	-0.626(0.100)	-0.631(0.068)
				Low	-0.649(0.105)	-0.649(0.063)
		Small	High	-0.705(0.121)	-0.643(0.078)	
			Low	-0.716(0.114)	-0.653(0.102)	

Appendix V

i. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
Hemisphere (Task Consistent) x Condition (Hemispherically Inconsistent)

Source	df	F
		Efficiency Score
Between Subjects		
Exposure Duration (E)	1	1.023
E between-groups		
error	28	(0.023)
E x Htc	1	0.436
Htc within-group		
error	28	(0.007)
E x Chi	1	8.523*
Chi within-group		
error	28	(0.002)
E x Htc x Chi	1	1.324
Htc x Chi within-group		
error	28	(0.001)

Within subjects

Hemisphere (task consistent)(Htc)	1	147.871**
Condition (hemispherically inconsistent)(Chi)	1	41.590**
Htc x Chi	1	17.226**

---

\*  $p < .05$ ; \*\* $p < .001$

ii. ANOVA Table of Transformed Efficiency Scores for Block 1, Female Participants,  
 Exposure Duration x Task x Hemisphere x Bin x Frequency

Source	<i>df</i>	<i>F</i> Efficiency Score
Between Subjects		
<i>Main Effects</i>		
Exposure Duration (E)	1	0.783
E between-group		
error	28	(0.091)
<i>Two-way Interactions</i>		
E x T	1	0.954
T within-group		
error	28	(0.020)
E x H	1	0.048
H within-group		
error	28	(0.002)
E x B	1	16.523**
B within-group		
error	28	(0.003)
E x F	1	0.735

F within-group		
error	28	(0.001)
<i>Three-way Interactions</i>		
E x T x H	1	1.593
T x H within-group		
error	28	(0.001)
E x T x B	1	9.184*
T x B within-group		
error	28	(0.002)
E x H x B	1	0.144
H x B within-group		
error	28	(0.001)
E x T x F	1	0.131
T x F within-group		
error	28	(0.001)
E x H x F	1	5.302*
H x F within-group		
error	28	(0.001)
E x B x F	1	0.259
B x F within-group		
error	28	(0.001)
<i>Four-way Interactions</i>		
E x T x H x B	1	0.360

T x H x B within-group		
error	28	(0.002)
E x T x H x F	1	0.074
T x H x F within-group		
error	28	(0.001)
E x T x B x F	1	1.085
T x B x F within-group		
error	28	(0.001)
E x H x B x F	1	1.727
H x B x F within-group		
error	28	(0.002)
<i>Five-way Interaction</i>		
E x T x H x B x F	1	0.497
T x H x B x F within-group		
error	28	(0.001)

---

Within subjects

*Main Effects*

Task (T)	1	213.294**
Hemisphere (H)	1	0.054
Bin Size (B)	1	37.056**
Frequency (F)	1	31.245**

*Two-way Interactions*

T x H	1	0.889
T x B	1	26.180**
T x F	1	0.585
H x B	1	1.286
H x F	1	0.931
B x F	1	0.196
<i>Three-way Interactions</i>		
T x H x B	1	0.144
T x H x F	1	0.863
T x B x F	1	0.002
H x B x F	1	0.166
<i>Four-way Interaction</i>		
T x H x B x F	1	1.669

---

\* $p < .05$ ; \*\* $p < .001$

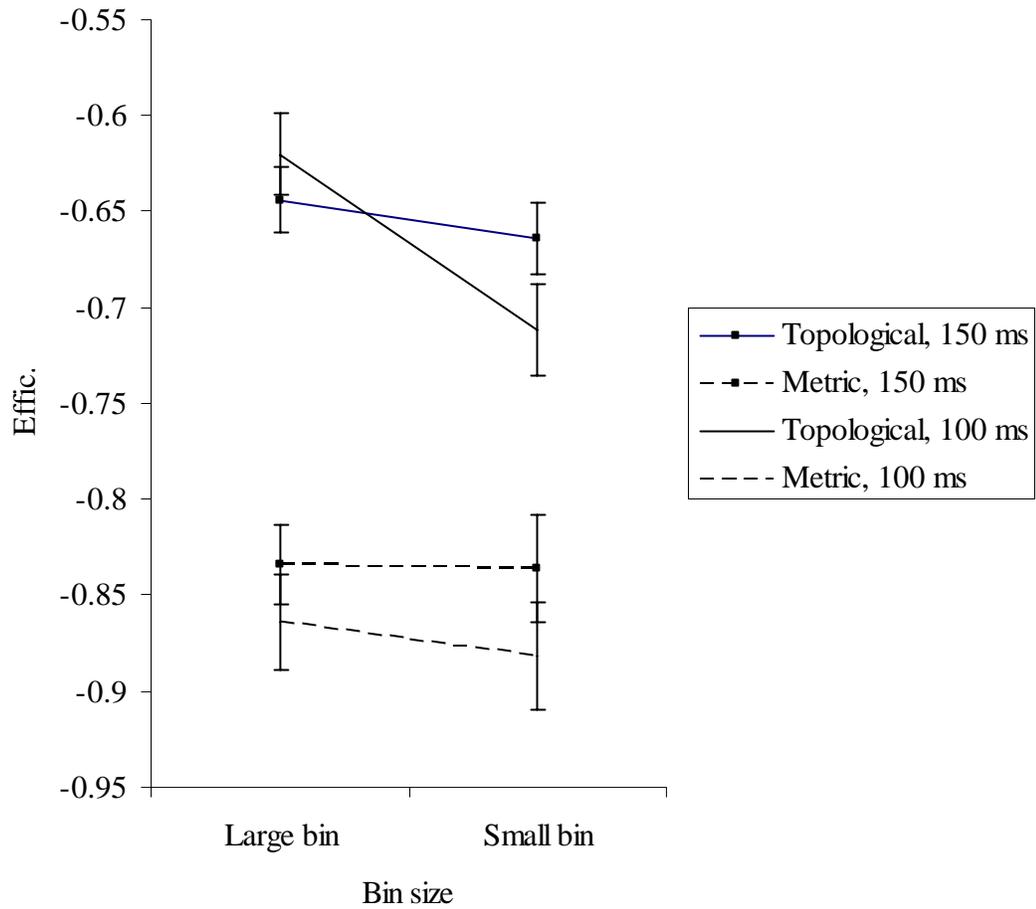


Figure Viii. Log transform efficiency means for female participants in block 1 showing a proportionally greater decrement under small bin compared to large bin conditions for the topological task when exposure duration was reduced. Effic. = Transformed efficiency scores.

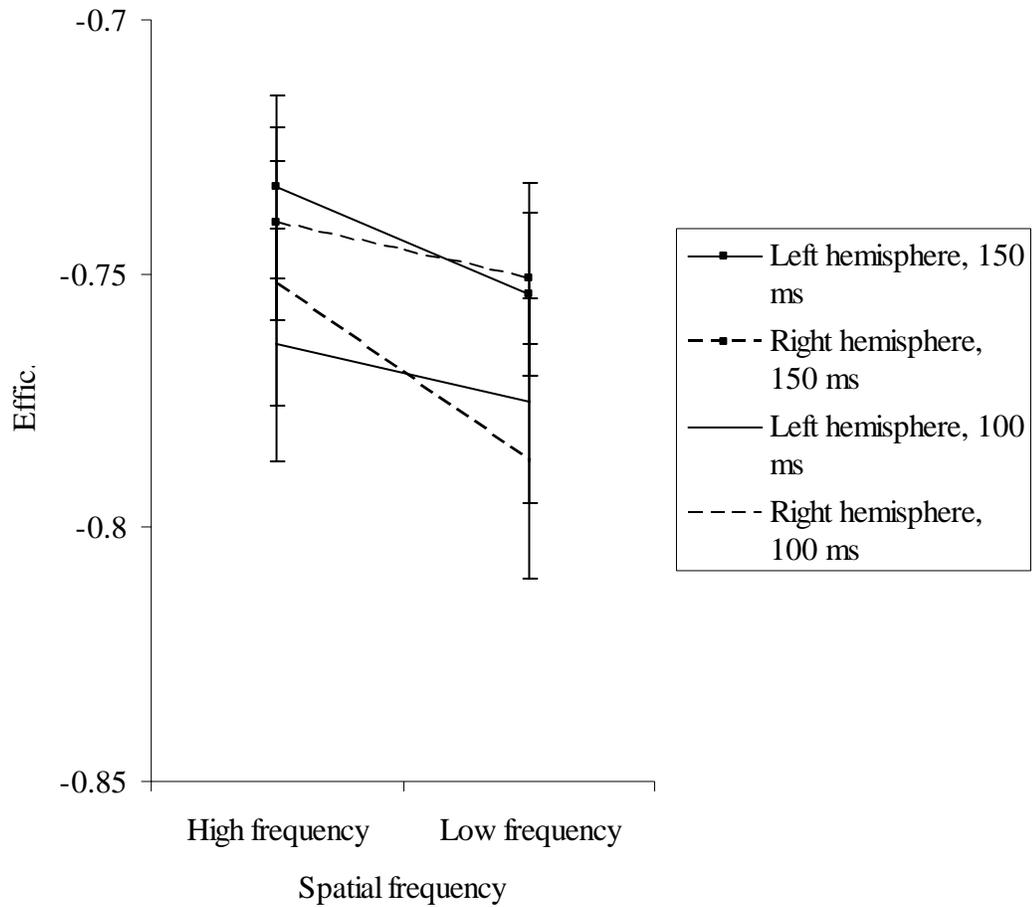


Figure Viv. Log transform efficiency means for female participants in block 1 showing a reversal of the left hemisphere advantage under high frequency at 150 ms to a right hemisphere advantage under high frequency at 100 ms and a reversal of the left hemisphere disadvantage under low frequency at 150 ms to a right hemisphere disadvantage under low frequency at 100 ms. Effic. = Transformed efficiency scores.

v. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
 Task x Hemisphere, Large Bin, High Frequency Conditions

Source	df	<i>F</i>
		Efficiency Score
Between Subjects		
Exposure Duration (E)	1	0.491
E between-group		
error	30	(0.027)
E x T	1	3.522
T within-group		
error	30	(0.005)
E x H	1	7.551*
H within-group		
error	30	(0.001)
E x T x H	1	0.117
T x H within-group		
error	30	(0.027)
Within subjects		
Task (T)	1	283.671**

Hemisphere (H)	1	0.039
T x H	1	0.003

---

\*  $p < .05$ ; \*\* $p < .001$

vi. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
 Task x Hemisphere, Large Bin, Low Frequency Conditions

Source	df	<i>F</i>
		Efficiency Score
Between Subjects		
Exposure Duration (E)	1	0.958
E between-groups		
error	30	(0.027)
E x T	1	0.694
T within-group		
error	30	(0.005)
E x H	1	2.043
H within-group		
error	30	(0.001)
E x T x H	1	1.909
T x H within-group		
error	30	(0.002)

Within subjects

Task (T)	1	253.518**
Hemisphere (H)	1	0.274
T x H	1	2.811
MSE	30	0.002

---

\*\* $p < .001$

vii. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
Task x Hemisphere, Small Bin, High Frequency Conditions

Source	df	F
		Efficiency Score
Between Subjects		
Exposure Duration (E)	1	3.229
E between-groups error	29	(0.032)
E x T	1	0.523
T within-group Error	29	(0.010)
E x H	1	0.823
H within-group Error	29	(0.003)
E x T x H	1	0.516
T x H within-group Error	29	(0.002)

Within subjects

Task (T)	1	80.334**
Hemisphere (H)	1	4.520
T x H	1	0.023

---

\*\* $p < .001$

viii. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
 Task x Hemisphere, Small Bin, Low Frequency Conditions

Source	df	<i>F</i>
		Efficiency Score
Between Subjects		
Exposure Duration (E)	1	3.238
E between-group		
error	28	(0.024)
E x T	1	0.005
T within-group		
error	28	(0.009)
E x H	1	0.113
H within-group		
error	28	(0.001)
E x T x H	1	0.000
T x H within-group		
error	28	(0.001)

Within subjects

Task (T)	1	91.114**
Hemisphere (H)	1	0.100
T x H	1	0.000

---

\*\* $p < .001$

ix. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)

Source	df	F
		Efficiency Score
Between Subjects		
Exposure Duration (E)	1	3.373
E between-group		
error	30	(0.034)
E x Htc	1	0.149
Htc within-group		
error	30	(0.011)
E x Chc	1	4.952*
Chc within-group		
error	30	(0.004)
E x Htc x Chc	1	9.170*
Htc x Chc within-group		
error	30	(0.034)
Within subjects		
Hemisphere (task consistent)(Htc)	1	89.456**

Condition (Hemispherically consistent)(Chc)	1	4.952*
Htc x Chc	1	14.635**

---

\*  $p < .05$ ; \*\* $p < .001$

*x. Means and Standard Deviations for Each Variable for Block 1, Female Participants  
for the 150 and 100 ms Exposure Duration Groups*

Variable				100 ms	150 ms
Task	Hemisphere	Bin	Frequency	M( <i>SD</i> )	M( <i>SD</i> )
Metric	Right	Large	High	-0.859(0.116)	-0.823(0.078)
			Low	-0.890(0.132)	-0.823(0.080)
		Small	High	-0.874(0.131)	-0.818(0.089)
			Low	-0.920 (0.141)	-0.840(0.070)
	Left	Large	High	-0.876(0.116)	-0.808(0.084)
			Low	-0.880(0.092)	-0.841(0.091)
		Small	High	-0.899(0.132)	-0.837(0.098)
			Low	-0.912(0.130)	-0.830(0.087)
Topological	Right	Large	High	-0.621(0.116)	-0.640(0.057)
			Low	-0.678(0.120)	-0.655(0.058)
		Small	High	-0.714(0.141)	-0.654(0.046)
			Low	-0.749(0.140)	-0.671(0.053)
	Left	Large	High	-0.643(0.125)	-0.622(0.061)
			Low	-0.663(0.136)	-0.641(0.061)
		Small	High	-0.769(0.197)	-0.651(0.053)
			Low	-0.722(0.121)	-0.669(0.053)

Appendix W

i. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants,  
Hemisphere (Task Consistent) x Condition (Hemispherically Inconsistent)

Source	df	F	
		Efficiency Score	
Between Subjects			
Exposure Duration (E)	1		0.051
E between-groups			
Error	22		0.028
E x Htc	1		0.328
Htc within-group			
Error	22		0.002
E x Chi	1		0.340
Chi within-group			
Error	22		0.001
E x Htc x Chi	1		4.395*
Htc x Chi within-group			
Error	22		0.028

Within subjects

Hemisphere (task consistent)(Htc)	1	325.014**
Condition (hemispherically inconsistent)(Chi)	1	13.382**
Htc x Chi	1	5.023*

---

\*  $p < .05$ ; \*\* $p < .001$

ii. ANOVA Table of Transformed Efficiency Scores for Block 2, Male Participants,  
 Exposure Duration x Task x Hemisphere x Bin x Frequency

Source	<i>df</i>	<i>F</i> Efficiency Score
Between Subjects		
<i>Main Effects</i>		
Exposure Duration (E)	1	3.539
E between-groups		
error	19	(0.040)
<i>Two-way Interactions</i>		
E x T	1	0.065
T within-group		
error	19	(0.008)
E x H	1	0.002
B within-group		
error	19	(0.002)
E x B	1	0.032
B within-group		
error	19	(0.002)
E x F	1	2.118

F within-group		
error	19	(0.001)
<i>Three-way Interactions</i>		
E x T x H	1	3.032
T x H within-group		
error	19	(0.001)
E x T x B	1	8.179*
T x B within-group		
error	19	(0.002)
E x H x B	1	2.438
H x B within-group		
error	19	(0.002)
E x T x F	1	0.199
T x F within-group		
error	19	(0.001)
E x H x F	1	0.032
H x F within-group		
error	19	(0.001)
E x B x F	1	1.209
B x F within-group		
error	19	(0.001)
<i>Four-way Interactions</i>		
E x T x H x B	1	0.436

T x H x B within-group		
error	19	(0.001)
E x T x H x F	1	0.022
T x H x F within-group		
error	19	(0.001)
E x T x B x F	1	0.455
T x B x F within-group		
error	19	(0.001)
E x H x B x F	1	1.490
H x B x F within-group		
error	19	(0.001)
<i>Five-way Interaction</i>		
E x T x H x B x F	1	2.426
T x H x B x F within-group		
error	19	(0.040)

---

Within subjects

*Main Effects*

Task (T)	1	297.347**
Hemisphere (H)	1	0.429
Bin Size (B)	1	11.016*
Frequency (F)	1	13.870**

*Two-way Interactions*

T x H	1	1.151
T x B	1	4.791*
T x F	1	9.677
H x B	1	0.192
H x F	1	0.280
B x F	1	5.830*
<i>Three-way Interactions</i>		
T x H x B	1	4.999*
T x H x F	1	2.792
T x B x F	1	4.607*
H x B x F	1	0.187
<i>Four-way Interaction</i>		
T x H x B x F	1	0.247

---

\* $p < .05$ ; \*\* $p < .001$

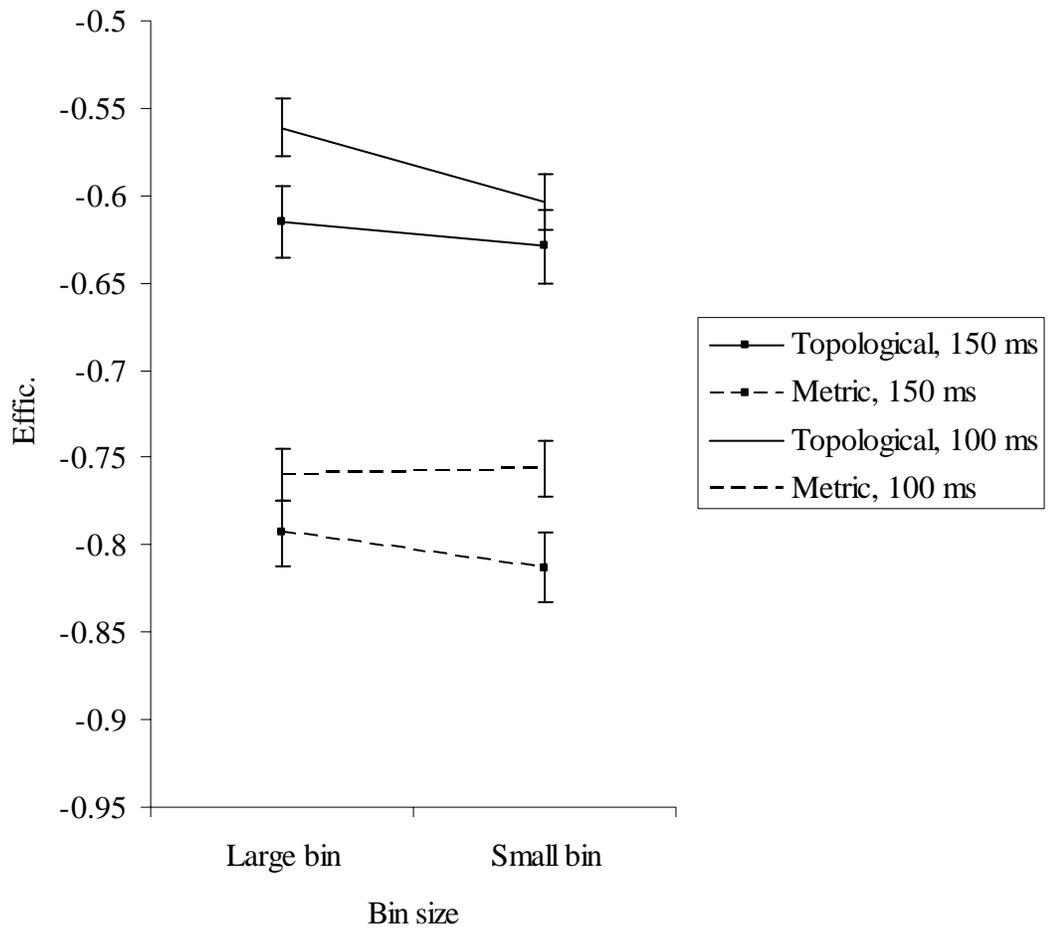


Figure Wiii. Log transform efficiency means for male participants in block 2 showing improved performance on the topological task under large bin conditions and improved performance on the metric task under small bin conditions when exposure duration was reduced. Effic. = Transformed efficiency scores.

iv. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants,  
 Task x Hemisphere, Large Bin, High Frequency Conditions

Source	df	<i>F</i>
		Efficiency Score
Between Subjects		
Exposure Duration (E)	1	1.501
E between-groups		
error	21	(0.020)
E x T	1	1.501
T within-group		
error	21	(0.003)
E x H	1	0.062
H within-group		
error	21	(0.001)
E x T x H	1	0.664
T x H within-group		
error	21	(0.001)
Within subjects		
Task (T)	1	299.053**
Hemisphere (H)	1	0.012

T x H

1

0.076

---

\*\* $p < .001$

v. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants, Task x Hemisphere, Large Bin, Low Frequency Conditions

Source	df	F	
		Efficiency Score	
Between Subjects			
Exposure Duration (E)	1		1.069
E between-groups			
error	20		(0.017)
E x T	1		1.504
T within-group			
error	20		(0.002)
E x H	1		1.762
H within-group			
error	20		(0.002)
E x T x H	1		2.715
T x H within-group			
error	20		(0.001)
Within subjects			
Task (T)	1		355.752**
Hemisphere (H)	1		0.756

T x H

1

1.038

---

\*\* $p < .001$

vi. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants,  
 Task x Hemisphere, Small Bin, High Frequency Conditions

Source	df	<i>F</i>
		Efficiency Score
Between Subjects		
Exposure Duration (E)	1	0.450
E between-groups		
error	21	(0.025)
E x T	1	1.116
T within-group		
error	21	(0.004)
E x H	1	0.194
H within-group		
error	21	(0.002)
E x T x H	1	2.560
T x H within-group		
error	21	(0.001)
Within subjects		
Task (T)	1	197.637**

Hemisphere (H)	1	0.002
T x H	1	5.210*

---

\*  $p < .05$ ; \*\* $p < .001$

vii. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants,  
 Task x Hemisphere, Small Bin, Low Frequency Conditions

Source	df	<i>F</i>
		Efficiency Score
Between Subjects		
Exposure Duration (E)	1	0.016
E between-groups		
error	21	(0.024)
E x T	1	1.309
T within-group		
error	21	(0.003)
E x H	1	1.890
H within-group		
error	21	(0.002)
E x T x H	1	0.004
T x H within-group		
error	21	(0.002)
Within subjects		
Task (T)	1	153.568**
Hemisphere (H)	1	0.023

T x H

1

0.068

---

\*\* $p < .001$

viii. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)

Source	df	F
		Efficiency Score
Between Subjects		
Exposure Duration (E)	1	0.750
E between-groups		
error	21	(0.026)
E x Htc	1	0.155
Htc within-group		
error	21	(0.002)
E x Chc	1	0.139
Chc within-group		
error	21	(0.002)
E x Htc x Chc	1	5.055*
Htc x Chc within-group		
error	21	(0.002)

Within subjects

Hemisphere (task consistent)(Htc)	1	419.228**
Condition (Hemispherically consistent)(Chc)	1	0.378
Htc x Chc	1	0.373**

---

\*  $p < .05$ ; \*\* $p < .001$

ix. Means and Standard Deviations for Each Variable for Block 2, Male Participants for the 150 and 100 ms Exposure Duration Groups

Variable				100 ms	150 ms	
Task	Hemisphere	Bin	Frequency	<i>M</i> ( <i>SD</i> )	<i>M</i> ( <i>SD</i> )	
Metric	Right	Large	High	-0.780(0.092)	-0.753(0.090)	
			Low	-0.801(0.094)	-0.789(0.087)	
		Small	High	-0.764(0.096)	-0.803(0.079)	
			Low	-0.776 (0.112)	-0.782(0.089)	
	Left	Large	High	-0.756(0.080)	-0.769(0.079)	
			Low	-0.767(0.077)	-0.778(0.083)	
		Small	High	-0.800(0.091)	-0.801(0.089)	
			Low	-0.793(0.105)	-0.800(0.059)	
	Topological	Right	Large	High	-0.560(0.092)	-0.604(0.067)
				Low	-0.598(0.088)	-0.596(0.076)
			Small	High	-0.616(0.102)	-0.613(0.078)
				Low	-0.630(0.086)	-0.641(0.066)
Left		Large	High	-0.563(0.100)	-0.584(0.085)	
			Low	-0.587(0.093)	-0.618(0.094)	
		Small	High	-0.591(0.117)	-0.589(0.083)	
			Low	-0.648(0.087)	-0.596(0.079)	

Appendix X

i. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants,  
Hemisphere (Task Consistent) x Condition (Hemispherically Inconsistent)

Source	df	F	
		Efficiency Score	
Between Subjects			
Exposure Duration (E)	1		0.275
E between-groups			
error	28		(0.030)
E x Htc	1		0.020
Htc within-group			
error	28		(0.004)
E x Chi	1		1.761
Chi within-group			
error	28		(0.004)
E x Htc x Chi	1		6.285*
Htc x Chi within-group			
error	28		(0.001)
Within subjects			
Hemisphere			

(task consistent)(Htc)	1	192.482**
Condition (hemispherically inconsistent)(Chi)	1	63.996**
Htc x Chi	1	18.551**

---

\*\* $p < .001$

ii. ANOVA Table of Transformed Efficiency Scores for Block 2, Female Participants,  
 Exposure Duration x Task x Hemisphere x Bin x Frequency

Source	<i>df</i>	<i>F</i> Efficiency Score
Between Subjects		
<i>Main Effects</i>		
Exposure Duration (E)	1	0.531
E between-groups		
error	26	(0.074)
<i>Two-way Interactions</i>		
E x T	1	0.055
T within-group		
error	26	(0.012)
E x H	1	0.007
H within-group		
error	26	(0.001)
E x B	1	7.244*
B within-group		
error	26	(0.006)
E x F	1	0.196

F within-group		
error	26	(0.002)
<i>Three-way Interactions</i>		
E x T x H	1	2.720
T x H within-group		
error	26	(0.001)
E x T x B	1	2.139
T x B within-group		
error	26	(0.005)
E x H x B	1	0.486
H x B within-group		
error	26	(0.001)
E x T x F	1	1.595
T x F within-group		
error	26	(0.001)
E x H x F	1	1.701
H x F within-group		
error	26	(0.001)
E x B x F	1	1.867
B x F within-group		
error	26	(0.001)
<i>Four-way Interactions</i>		
E x T x H x B	1	4.880*

T x H x B within-group		
error	26	(0.001)
E x T x H x F	1	0.108
T x H x F within-group		
error	26	(0.001)
E x T x B x F	1	0.241
T x B x F within-group		
error	26	(0.001)
E x H x B x F	1	0.003
H x B x F within-group		
error	26	(0.001)
<i>Five-way Interaction</i>		
E x T x H x B x F	1	0.123
T x H x B x F within-group		
error	26	(0.001)

---

Within subjects

*Main Effects*

Task (T)	1	224.107**
Hemisphere (H)	1	0.218
Bin Size (B)	1	23.724**
Frequency (F)	1	26.623**

*Two-way Interactions*

T x H	1	2.164
T x B	1	7.979*
T x F	1	6.689*
H x B	1	0.076
H x F	1	0.144
B x F	1	1.099
<i>Three-way Interactions</i>		
T x H x B	1	1.522
T x H x F	1	4.251*
T x B x F	1	0.851
H x B x F	1	0.714
<i>Four-way Interaction</i>		
T x H x B x F	1	8.375

---

\* $p < .05$ ; \*\* $p < .001$

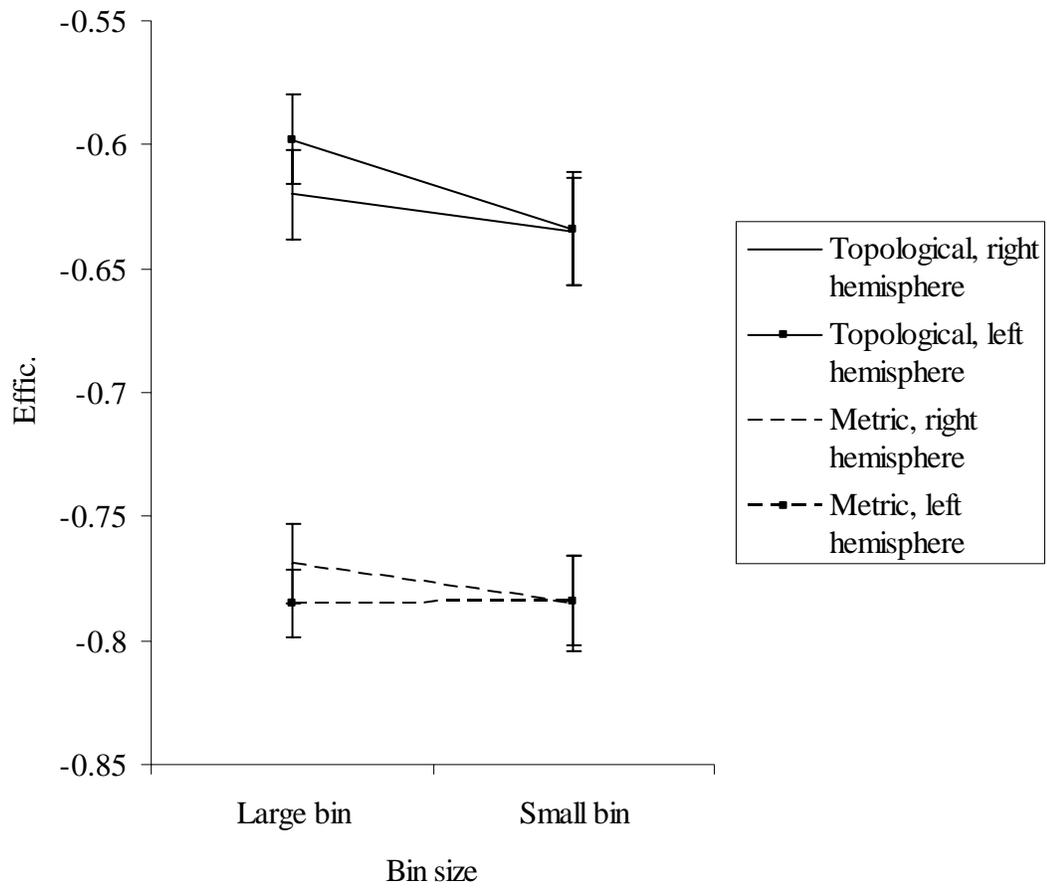


Figure Xiii. Log transformed efficiency scores for female participants in block 2

showing that at 150 ms, the topological task is performed better with the left hemisphere than the right when bin size is large but the metric task is performed better with the right hemisphere than the left when bin size is large. Effic. = Transformed efficiency scores.

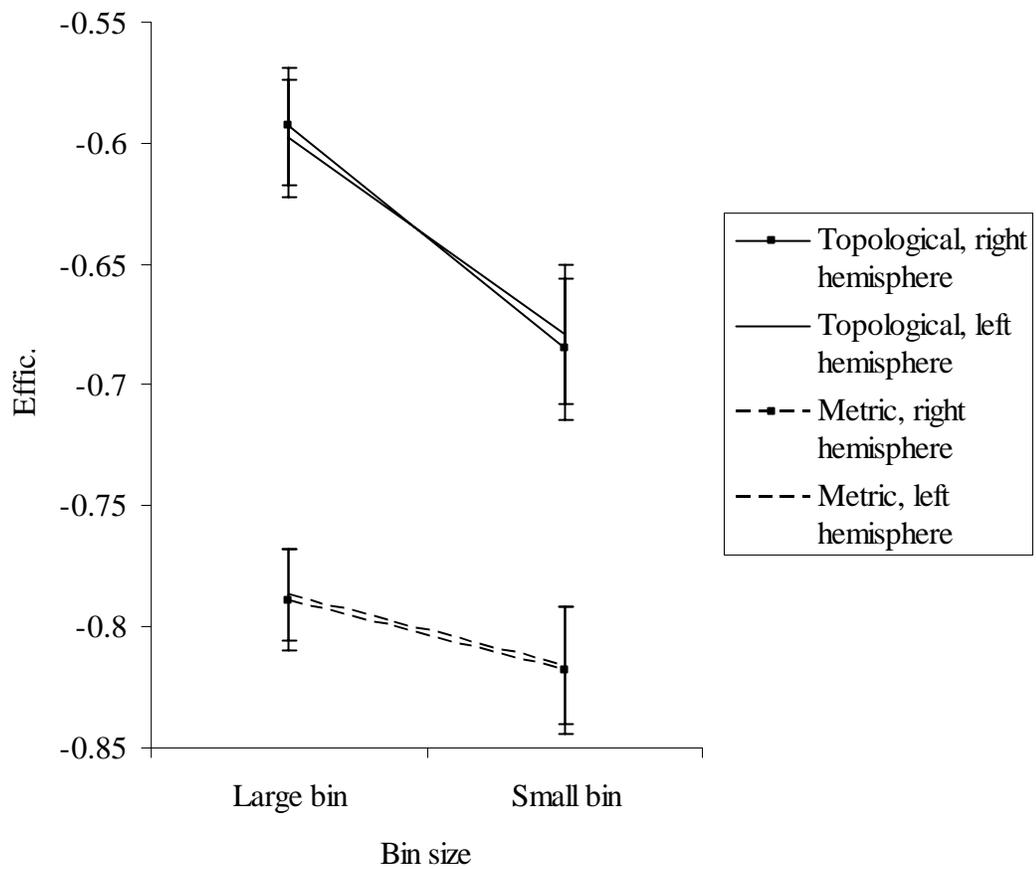


Figure Xiv. Log transformed efficiency scores for female participants in block 2 showing that at 100 ms, the task are performed as well by either hemisphere under both large and small bins. Effic. = Transformed efficiency scores.

v. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants,  
 Task x Hemisphere, Large Bin, High Frequency Conditions

Source	df	<i>F</i>
		Efficiency Score
<u>Between Subjects</u>		
Exposure Duration (E)	1	0.038
E between-group		
error	28	(0.022)
E x T	1	2.806
T within-group		
error	28	(0.004)
E x H	1	0.002
H within-group		
error	28	(0.001)
E x T x H	1	0.117
T x H within-group		
error	28	(0.001)
<u>Within subjects</u>		
Task (T)	1	302.395**
Hemisphere (H)	1	0.678

T x H	1	5.340*
-------	---	--------

---

\*  $p < .05$ ; \*\* $p < .001$

vi. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants,  
 Task x Hemisphere, Large Bin, Low Frequency Conditions

Source	df	F
		Efficiency Score
Between Subjects		
Exposure Duration (E)	1	0.059
E between-groups		
Error	29	(0.025)
E x T	1	0.924
T within-group		
Error	29	(0.004)
E x H	1	1.888
H within-group		
Error	29	0.001
E x T x H	1	2.591
T x H within-group		
Error	29	(0.001)
Within subjects		
Task (T)	1	212.837**

Hemisphere (H)	1	0.260
T x H	1	6.540*

---

\*  $p < .05$ ; \*\* $p < .001$

vii. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants,  
 Task x Hemisphere, Small Bin, High Frequency Conditions

Source	df	<i>F</i>
		Efficiency Score
Between Subjects		
Exposure Duration (E)	1	0.919
E between-groups		
error	27	(0.025)
E x T	1	0.273
T within-group		
error	27	(0.005)
E x H	1	0.979
H within-group		
error	27	(0.001)
E x T x H	1	0.007
T x H within-group		
error	27	(0.001)
Within subjects		
Task (T)	1	111.993**

Hemisphere (H)	1	0.164
T x H	1	6.392*

---

\*  $p < .05$ ; \*\* $p < .001$

viii. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants,  
 Task x Hemisphere, Small Bin, Low Frequency Conditions

Source	df	F
		Efficiency Score
Between Subjects		
Exposure Duration (E)	1	1.027
E between-groups		
error	28	0.036
E x T	1	1.068
T within-group		
error	28	(0.005)
E x H	1	0.864
H within-group		
error	28	(0.001)
E x T x H	1	0.003
T x H within-group		
error	28	(0.002)
<u>Within subjects</u>		
Task (T)	1	96.343**

Hemisphere (H)	1	0.009
T x H	1	2.870

---

**\*\* $p < .001$**

ix. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants,  
Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)

Source	df	<i>F</i>
		Efficiency Score
<b>Between Subjects</b>		
Exposure Duration (E)	1	0.001
E between-groups		
error	28	(0.025)
E x Htc	1	0.138
Htc within-group		
error	28	(0.004)
E x Chc	1	1.995
Chc within-group		
error	28	(0.002)
E x Htc x Chc	1	0.152
Htc x Chc within-group		
error	28	(0.002)
<b><u>Within subjects</u></b>		
Hemisphere (task consistent)(Htc)	1	198.283**

Condition (Hemispherically consistent)(Chc)	1	1.995
Htc x Chc	1	1.855

---

**\*\* $p < .001$**

*x. Means and Standard Deviations for Each Variable for Block 2, Female Participants  
for the 150 and 100 ms Exposure Duration Groups*

Variable				100 ms	150 ms
Task	Hemisphere	Bin	Frequency	<i>M</i> ( <i>SD</i> )	<i>M</i> ( <i>SD</i> )
Metric	Right	Large	High	-0.784(0.098)	-0.756(0.071)
			Low	-0.774(0.094)	-0.768(0.065)
		Small	High	-0.780(0.124)	-0.768(0.063)
			Low	-0.787 (0.143)	-0.802(0.075)
	Left	Large	High	-0.773(0.100)	-0.770(0.065)
			Low	-0.794(0.103)	-0.784(0.063)
		Small	High	-0.778(0.130)	-0.784(0.069)
			Low	-0.798(0.125)	-0.775(0.077)
Topological	Right	Large	High	-0.552(0.112)	-0.604(0.076)
			Low	-0.588(0.108)	-0.628(0.082)
		Small	High	-0.680(0.148)	-0.624(0.063)
			Low	-0.675(0.136)	-0.641(0.070)
	Left	Large	High	-0.548(0.104)	-0.584(0.073)
			Low	-0.590(0.128)	-0.598(0.087)
		Small	High	-0.616(0.140)	-0.616(0.066)
			Low	-0.674(0.167)	-0.637(0.095)

Appendix Y

i. ANOVA Table of Transformed Efficiency Scores for 5 Within (Block, Task, Hemisphere, Bin, Frequency) and 1 Between (Sex) for 100 ms Exposure Duration

Source	df	<i>F</i>
		Efficiency Score
Between Subjects		
<i>Main Effects</i>		
Sex(S)	1	1.144
S between-groups		
error	16	(0.136)
<i>Two-way Interactions</i>		
S x Bl	1	1.679
Bl within-group		
error	16	(0.020)
S x T	1	0.419
T within-group		
error	16	(0.020)
S x H	1	0.422
H within-group		
error	16	(0.003)

S x B	1	0.848
B within-group		
error	16	(0.009)
S x F	1	0.735
F within-group		
error	16	(0.002)
<i>Three-way Interactions</i>		
S x Bl x T	1	6.862*
Bl x T within-group		
error	16	(0.005)
S x Bl x H	1	0.002
Bl x H within-group		
error	16	(0.002)
S x T x H	1	0.458
T x H within-group		
error	16	(0.002)
S x Bl x B	1	0.064
Bl x B within-group		
error	16	(0.003)
S x T x B	1	1.415
T x B within-group		
error	16	(0.001)
S x H x B	1	0.669

H x B within-group		
error	16	(0.003)
S x Bl x F	1	0.758
Bl x F within-group		
error	16	(0.001)
S x T x F	1	0.003
T x F within-group		
error	16	(0.001)
S x H x F	1	0.049
H x F within-group		
error	16	(0.002)
S x B x F	1	0.294
B x F within-group		
error	16	(0.002)
<i>Four-way Interactions</i>		
S x Bl x T x H	1	5.393*
Bl x T x H within-group		
error	16	(0.001)
S x Bl x T x B	1	4.747*
Bl x T x B within-group		
error	16	(0.003)
S x Bl x H x B	1	0.222
Bl x H x B within-group		

error	16	(0.001)
S x T x H x B	1	0.346
T x H x B within-group		
error	16	(0.001)
S x Bl x T x F	1	0.595
Bl x T x F within-group		
error	16	(0.002)
S x Bl x H x F	1	0.360
Bl x H x F within-group		
error	16	(0.001)
S x T x H x F	1	1.379
T x H x F within-group		
error	16	(0.001)
S x Bl x B x F	1	0.146
Bl x B x F within-group		
error	16	(0.001)
S x T x B x F	1	0.571
T x B x F within-group		
error	16	(0.002)
S x H x B x F	1	0.358
H x B x F within-group		
error	16	(0.002)

*Five-way Interactions*

S x Bl x T x H x B	1	1.411
Bl x T x H x B within-group		
error	16	(0.002)
S x Bl x T x H x F	1	0.120
Bl x T x H x F within-group		
error	16	(0.002)
S x Bl x T x B x F	1	1.925
Bl x T x B x F within-group		
error	16	(0.001)
S x Bl x H x B x F	1	0.109
Bl x H x B x F within-group		
error	16	(0.002)
S x T x H x B x F	1	0.928
T x H x B x F within-group		
error	16	(0.001)
<i>Six-way Interactions</i>		
S x Bl x T x H x B x F	1	0.769
Bl x T x H x B x F within-group		
error	16	(0.001)

---

Within subjects

*Main Effects*

Block (Bl)	1	239.028**
Task (T)	1	27.044**
Hemisphere (H)	1	0.052
Bin Size (B)	1	20.479**
Frequency (F)	1	39.642**
<i>Two-way Interactions</i>		
Bl x T	1	1.554
Bl x H	1	0.375
Bl x B	1	20.038
Bl x F	1	3.351
<i>Three-way Interactions</i>		
Bl x T x H	1	0.307
Bl x T x B	1	1.121
Bl x H x B	1	4.779*
Bl x T x F	1	2.672
Bl x H x F	1	1.780
Bl x B x F	1	0.047
<i>Four-way Interactions</i>		
Bl x T x H x B	1	0.028
Bl x T x H x F	1	0.549
Bl x T x B x F	1	2.686
Bl x H x B x F	1	3.065
<i>Five-way Interaction</i>		

Bl x T x H x B x F

1

0.047

---

\*\* $p < .001$ ; \* $p < .05$

ii. Means and Standard Deviations for Female Participants at 100 ms for Each Variable and Each Block with Significant Between Block Differences Indicated.

Variable				Block 1	Block 2	
Task	Hemisphere	Bin	Frequency	<i>M</i> ( <i>SD</i> )	<i>M</i> ( <i>SD</i> )	
Metric	Right	Large	High	-0.887(0.101)	-0.784(0.098)*	
			Low	-0.890(0.132)	-0.774(0.093)*	
		Small	High	-0.872(0.119)	-0.780(0.124)	
			Low	-0.920 (0.141)	-0.787(0.143)*	
		Left	Large	High	-0.889(0.109)	-0.773 (0.099)*
				Low	-0.892(0.083)	-0.794(0.103)*
	Topological	Right	Large	High	-0.621(0.116)	-0.552(0.112)
				Low	-0.678(0.120)	-0.558(0.108)
			Small	High	-0.725(0.143)	-0.662(0.139)
				Low	-0.756(0.114)	-0.667(0.139)
		Left	Large	High	-0.643(0.125)	-0.549(0.104)
				Low	-0.663(0.136)	-0.590(0.128)
		Small	High	-0.764(0.204)	-0.616(0.140)	
			Low	-0.722(0.121)	-0.653(0.166)	

iii. Means and Standard Deviations for Male Participants at 100 ms for Each Variable and Each Block with Significant Between Block Differences Indicated.

Variable				Block 1	Block 2
Task	Hemisphere	Bin	Frequency	<i>M</i> ( <i>SD</i> )	<i>M</i> ( <i>SD</i> )
Metric	Right	Large	High	-0.846(0.121)	-0.780(0.092)
			Low	-0.846(0.108)	-0.801(0.094)
		Small	High	-0.853(0.134)	-0.764(0.096)*
			Low	-0.878 (0.149)	-0.776(0.112)
	Left	Large	High	-0.820(0.084)	-0.756(0.080)
			Low	-0.823(0.085)	-0.770(0.079)
		Small	High	-0.874(0.115)	-0.800(0.091)
			Low	-0.872(0.096)	-0.802(0.103)
Topological	Right	Large	High	-0.619(0.013)	-0.568(0.091)*
			Low	-0.661(0.085)	-0.616(0.079)
		Small	High	-0.705(0.102)	-0.638(0.088)*
			Low	-0.707(0.093)	-0.650(0.070)*
	Left	Large	High	-0.626(0.099)	-0.574(0.090)*
			Low	-0.662(0.096)	-0.560(0.083)*
		Small	High	-0.705(0.121)	-0.602(0.112)*
			Low	-.0716(0.114)	-0.657(0.083)*

\* $p \leq .002$

Appendix Z

i. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants,  
Hemisphere(Task Consistent) x Condition (Hemispherically Inconsistent)

---

Source	df	F
		Efficiency Score
Within subjects		
Hemisphere (task consistent)(Htc)	1	90.985**
Condition (hemispherically consistent)(Chc)	1	16.826**
Htc x Chc	1	1.264
Htc x Chc within-group error	13	(0.003)

---

\*\* $p < .001$

ii. ANOVA Table of Transformed Efficiency Scores for Block 1, Male Participants, Task  
*x Hemisphere x Bin x Frequency*

Source	<i>df</i>	<i>F</i>
		Efficiency Score
Within subjects		
<i>Main Effects</i>		
Task (T)	1	164.890**
T within-group		
error	11	(0.008)
Hemisphere (H)	1	0.589
H within-group		
error	11	(0.002)
Bin Size (B)	1	18.283**
B within-group		
error	11	(0.005)
Frequency (F)	1	2.849
F within-group		
error	11	(0.002)

*Two-way Interactions*

T x H	1	3.175
T x H within-group		
error	11	(0.002)
T x B	1	5.288*
T x B within-group		
error	11	(0.003)
T x F	1	0.003
T x F within-group		
error	11	(0.002)
H x B	1	0.167
H x B within-group		
error	11	(0.001)
H x F	1	3.324
H x F within-group		
error	11	(0.001)
B x F	1	2.694
B x F within-group		
error	11	(0.001)

*Three-way Interactions*

T x H x B	1	0.001
T x H x B within-group		
error	11	(0.001)

T x H x F	1	0.090
T x H x F within-group		
error	11	(0.003)
T x B x F	1	1.383
T x B x F within-group		
error	11	(0.001)
H x B x F	1	1.781
H x B x F within-group		
error	11	(0.002)
<i>Four-way Interaction</i>		
T x H x B x F	1	1.212
T x H x B x F within-group		
error	11	(0.002)

---

\*\* $p < .001$ ; \* $p < .05$

iii. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants,  
 Task x Hemisphere, Large Bin, High Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	92.494**	
Hemisphere (H)	1	0.128	
T x H	1	1.856	
T x H within-group			
error	13	(0.001)	

\*\* $p < .001$

iv. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants,  
 Task x Hemisphere, Large Bin, Low Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	102.779**	
Hemisphere (H)	1	0.008	
T x H	1	0.015	
T x H within-group			
error	12	(0.002)	

\*\* $p < .001$

v. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants, Task x Hemisphere, Small Bin, High Frequency Conditions

Source	df	F
		Efficiency Score
Within subjects		
Task (T)	1	91.966**
Hemisphere (H)	1	3.005
T x H	1	0.191
T x H within-group		
error	13	(0.001)

\*\* $p < .001$

vi. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants,  
 Task x Hemisphere, Small Bin, Low Frequency Conditions

Source	df	F
		Efficiency Score
Within subjects		
Task (T)	1	88.961**
Hemisphere (H)	1	2.670
T x H	1	2.528
T x H within-group		
error	12	(0.004)

\*\* $p < .001$

vii. ANOVA Table for Transformed Efficiency Scores for Block 1, Male Participants,  
Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)

Source	df	F
		Efficiency Score
Within subjects		
Hemisphere (task consistent)(Htc)	1	68.548**
Condition (Hemispherically consistent)(Chc)	1	3.053
Htc x Chc	1	7.569*
Htc x Chc within-group error	14	(0.002)

\*\*p. < .001

viii. Means and Standard Deviations for Each Variable for Block 1, Male Participants.

---

Variable				
Task	Hemisphere	Bin	Frequency	<i>M</i> ( <i>SD</i> )
Metric	Right	Large	High	-0.846(0.121)
			Low	-0.846(0.108)
		Small	High	-0.853(0.133)
			Low	-0.878 (0.149)
	Left	Large	High	-0.836(.0103)
			Low	-0.839(.0102)
		Small	High	-0.863(.0120)
			Low	-0.872(.0096)
Topological	Right	Large	High	-0.619(.0093)
			Low	-0.661(.0085)
		Small	High	-0.705(.0102)
			Low	-0.707(.0093)
	Left	Large	High	-0.626(.0100)
			Low	-.0.649(0.105)
		Small	High	-0.705(0.121)
			Low	-0.716(0.114)

---

Appendix AA

i. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
Hemisphere (Task Consistent) x Condition (Hemispherically Inconsistent)

Source	<i>df</i>	<i>F</i> Efficiency Score
Within subjects		
Hemisphere (task consistent)(Htc)	1	34.087**
Condition (hemispherically consistent)(Chi)	1	31.434**
Htc x Chi	1	7.469
Htc x Chi within-group error	11	(0.002)

\*\* $p < .001$

ii. ANOVA Table of Transformed Efficiency Scores for Block 1 Female Participants,  
 Task x Hemisphere x Bin x Frequency

Source	df	<i>F</i>
		Efficiency Score
Within subjects		
<i>Main Effects</i>		
Task (T)	1	101.925**
T within-group		
error	11	(0.036)
Hemisphere (H)	1	0.045
H within-group		
error	11	(0.003)
Bin Size (B)	1	9.387*
B within-group		
error	11	(0.006)
Frequency (F)	1	8.155*
F within-group		
error	11	(0.002)

*Two-way Interactions*

T x H	1	0.009
T x H within-group		
error	9	(0.001)
T x B	1	3.060
T x B within-group		
error	9	(0.011)
T x F	1	3.417
T x F within-group		
error	9	(0.002)
H x B	1	0.193
H x B within-group		
error	9	(0.002)
H x F	1	0.865
H x F within-group		
error	9	(0.001)
B x F	1	1.299
B x F within-group		
error	9	(0.003)

*Three-way Interactions*

T x H x B	1	0.306
T x H x B within-group		
error	9	(0.001)

T x H x F	1	1.844
T x H x F within-group		
error	9	(0.001)
T x B x F	1	0.443
T x B x F within-group		
error	9	(0.002)
H x B x F	1	0.238
H x B x F within-group		
error	9	(0.001)
<i>Four-way Interaction</i>		
T x H x B x F	1	2.074
T x H x B x F within-group		
error	9	(0.001)

---

\*\* $p < .001$ ; \* $p < .05$

iii. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
 Task x Hemisphere, Large Bin, High Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	164.276**	
Hemisphere (H)	1	0.057	
T x H	1	0.094	
T x H within-group			
error	11	(0.001)	

\*\* $p < .001$

iv. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
 Task x Hemisphere, Large Bin, Low Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	145.228**	
Hemisphere (H)	1	1.010	
T x H	1	0.249	
T x H within-group			
error	12	(0.001)	

\*\* $p < .001$

v. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
 Task x Hemisphere, Small Bin, High Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	22.642**	
Hemisphere (H)	1	0.455	
T x H	1	1.574	
T x H within-group			
error	10	(0.001)	

\*\* $p < .001$

vi. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
 Task x Hemisphere, Small Bin, Low Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	23.085**	
Hemisphere (H)	1	0.332	
T x H	1	1.004	
T x H within-group			
error	11	(0.002)	

\*\* $p < .001$

vii. ANOVA Table for Transformed Efficiency Scores for Block 1, Female Participants,  
Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)

Source	df	F	
		Efficiency Score	
Within subjects			
Hemisphere (task consistent)(Htc)	1	91.952**	
Condition (Hemispherically consistent)(Chc)	1	1.540	
Htc x Chc	1	0.649	
Htc x Chc within-group error	11	(0.005)	

\*\* $p < .001$

viii. Means and Standard Deviations for Each Variable for Block 1, Female

Participants.

---

Variable				
Task	Hemisphere	Bin	Frequency	<i>M</i> ( <i>SD</i> )
Metric	Right	Large	High	-0.859(0.116)
			Low	-0.890(0.132)
		Small	High	-0.874(0.131)
			Low	-0.920 (0.141)
	Left	Large	High	-0.876(0.116)
			Low	-0.880(0.092)
		Small	High	-0.899(0.132)
			Low	-0.912(0.130)
Topological	Right	Large	High	-0.621(0.116)
			Low	-0.678(0.120)
		Small	High	-0.714(0.141)
			Low	-0.749(0.140)
	Left	Large	High	-0.643(0.125)
			Low	-0.663(0.136)
		Small	High	-0.769(0.197)
			Low	-0.722(0.121)

---

Appendix BB

i. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants,  
Hemisphere (Task Consistent) x Condition (Hemispherically Inconsistent)

Source	<i>df</i>	<i>F</i> Efficiency Score
Within subjects		
Hemisphere (task consistent)(Htc)	1	222.621**
Condition (hemispherically consistent)(Chi)	1	12.910*
Htc x Chi	1	9.563*
Htc x Chi within-group error	14	(0.003)

\*\* $p < .001$

ii. ANOVA Table of Transformed Efficiency Scores for Block 2, Male Participants, Task  
*x Hemisphere x Bin x Frequency*

Source	<i>df</i>	<i>F</i>
		Efficiency Score
Within subjects		
<i>Main Effects</i>		
Task (T)	1	224.693**
T within-group		
error	12	(0.007)
Hemisphere (H)	1	0.232
H within-group		
error	12	(0.003)
Bin Size (B)	1	7.969*
B within-group		
error	12	(0.002)
Frequency (F)	1	14.362*
F within-group		
error	12	(0.001)

*Two-way Interactions*

T x H	1	6.093*
T x H within-group		
error	12	(0.001)
T x B	1	11.326*
T x B within-group		
error	12	(0.003)
T x F	1	8.303
T x F within-group		
error	12	(0.001)
H x B	1	1.706
H x B within-group		
error	12	(0.001)
H x F	1	0.323
H x F within-group		
error	12	(0.001)
B x F	1	0.791
B x F within-group		
error	12	(0.001)

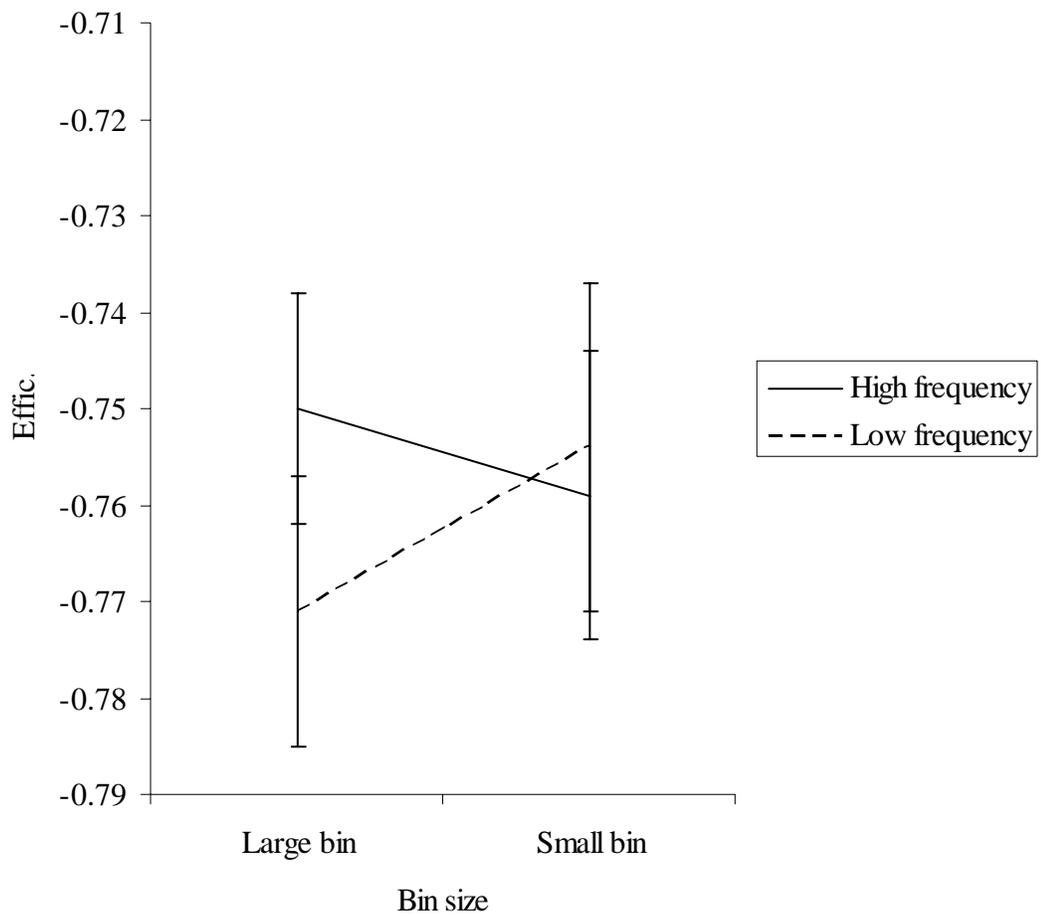
*Three-way Interactions*

T x H x B	1	5.107*
T x H x B within-group		
error	12	(0.001)

T x H x F	1	2.139
T x H x F within-group		
error	12	(0.001)
T x B x F	1	4.570*
T x B x F within-group		
error	12	(0.001)
H x B x F	1	1.946
H x B x F within-group		
error	12	(0.001)
<i>Four-way Interaction</i>		
T x H x B x F	1	2.382
T x H x B x F within-group		
error	12	(0.002)

---

\*\* $p < .001$ ; \* $p < .05$



**Figure BBiii.** Mean log transformed efficiency scores for male participants in block 2 for the topological task showing a bin x frequency interaction with better performance under large bin conditions when frequency was high and better performance under small bin conditions when frequency was low. Effic. = Transformed efficiency scores.

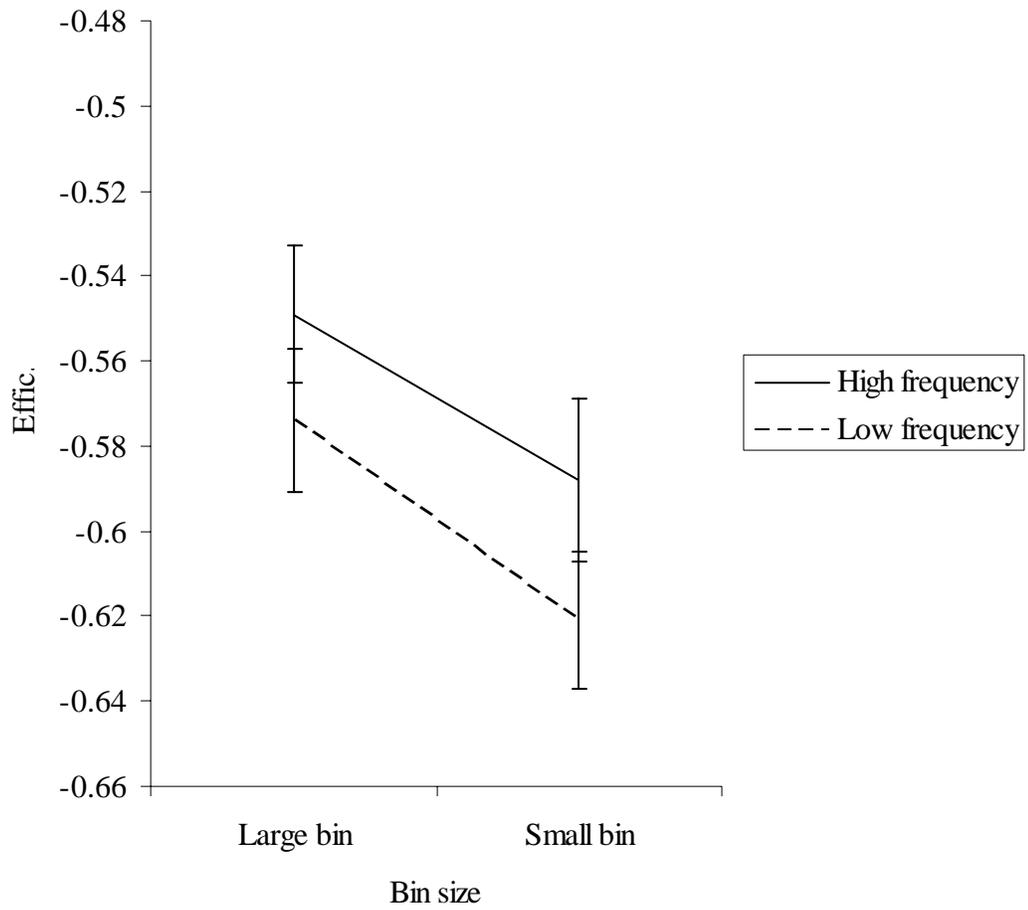


Figure BBiv. Mean log transformed efficiency scores for male participants in block 2 for the metric task showing no significant bin x frequency interaction. Effic. = Transformed efficiency scores.

v. ANOVA Table for Transformed Efficiency Scores for Block 2 Male Participants, Task x Hemisphere, Large Bin, High Frequency Conditions

Source	df	F
		Efficiency Score
Within subjects		
Task (T)	1	253.837**
Hemisphere (H)	1	0.082
T x H	1	0.729
T x H within-group error	14	(0.001)

\*\* $p < .001$

vi. ANOVA Table for Transformed Efficiency Scores for Block 2 Male Participants,  
 Task x Hemisphere, Large Bin, Low Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	338.351**	
Hemisphere (H)	1	2.405	
T x H	1	0.246	
T x H within-group			
error	13	(0.001)	

\*\* $p < .001$

vii. ANOVA Table for Transformed Efficiency Scores for Block 2 Male Participants,  
 Task x Hemisphere, Small Bin, High Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	113.312**	
Hemisphere (H)	1	0.089	
T x H	1	10.899*	
T x H within-group			
error	14	(0.001)	

\*\* $p < .001$

viii. ANOVA Table for Transformed Efficiency Scores for Block 2 Male Participants,  
 Task x Hemisphere, Small Bin, Low Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	97.155**	
Hemisphere (H)	1	1.034	
T x H	1	0.095	
T x H within-group			
error	14	(0.001)	

\*\* $p < .001$

ix. ANOVA Table for Transformed Efficiency Scores for Block 2, Male Participants,  
Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)

Source	df	F
		Efficiency Score
Within subjects		
Hemisphere (task consistent)(Htc)	1	335.105**
Condition (Hemispherically consistent)(Chc)	1	0.692
Htc x Chc	1	4.393*
Htc x Chc within-group error	14	(0.002)

\*\* $p < .001$

x. Means and Standard Deviations for Each Variable for Block 2, Male Participants.

---

Variable				
Task	Hemisphere	Bin	Frequency	<i>M</i> ( <i>SD</i> )
Metric	Right	Large	High	-0.780(0.092)
			Low	-0.801(0.094)
		Small	High	-0.764(0.096)
			Low	-0.776(0.112)
	Left	Large	High	-0.756(0.080)
			Low	-0.767(0.077)
		Small	High	-0.800(0.091)
			Low	-0.793(0.105)
Topological	Right	Large	High	-0.560(0.092)
			Low	-0.598(0.088)
		Small	High	-0.616(0.102)
			Low	-0.630(0.086)
	Left	Large	High	-0.563(0.097)
			Low	-0.587(0.093)
		Small	High	-0.591(0.117)
			Low	-0.648(0.087)

---

Appendix CC

i. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants,  
Hemisphere (Task Consistent) x Condition (Hemispherically Inconsistent)

Source	<i>df</i>	<i>F</i> Efficiency Score
Within subjects		
Hemisphere (task consistent)(Htc)	1	72.370**
Condition (hemispherically consistent)(Chi)	1	13.712*
Htc x Chi	1	13.732*
Htc x Chi within-group error	11	(0.002)

\*  $p < .05$ ; \*\* $p < .001$

ii. ANOVA Table of Transformed Efficiency Scores for Block 2, Female Participants,  
 Task x Hemisphere x Bin x Frequency

Source	df	<i>F</i>
		Efficiency Score
Within subjects		
<i>Main Effects</i>		
Task (T)	1	224.693**
T within-group		
error	9	(0.011)
Hemisphere (H)	1	0.232
H within-group		
error	9	(0.002)
Bin Size (B)	1	7.969*
B within-group		
error	9	(0.014)
Frequency (F)	1	14.362*
F within-group		
error	9	(0.002)
<i>Two-way Interactions</i>		
T x H	1	6.093*

T x H within-group		
error	12	(0.001)
T x B	1	11.326*
T x B within-group		
error	12	(0.003)
T x F	1	8.303
T x F within-group		
error	12	(0.001)
H x B	1	1.706
H x B within-group		
error	12	(0.001)
H x F	1	0.323
H x F within-group		
error	12	(0.001)
B x F	1	0.791
B x F within-group		
error	12	(0.001)
<i>Three-way Interactions</i>		
T x H x B	1	5.107*
T x H x B within-group		
error	12	(0.001)
T x H x F	1	2.139
T x H x F within-group		

error	12	(0.001)
T x B x F	1	4.570*
T x B x F within-group		
error	12	(0.001)
H x B x F	1	1.946
H x B x F within-group		
error	12	(0.001)
<i>Four-way Interaction</i>		
T x H x B x F	1	2.382
T x H x B x F within-group		
error	12	(0.002)

---

\*\* $p < .001$ ; \* $p < .05$

iii. ANOVA Table for Transformed Efficiency Scores for Block 2 Female Participants,  
 Task x Hemisphere, Large Bin, High Frequency Conditions

Source	df	F
		Efficiency Score
Within subjects		
Task (T)	1	253.837**
Hemisphere (H)	1	0.082
T x H	1	0.729
T x H within-group		
error	14	(0.001)

\*\* $p < .001$

iv. ANOVA Table for Transformed Efficiency Scores for Block 2 Female Participants,  
 Task x Hemisphere, Large Bin, Low Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	338.351**	
Hemisphere (H)	1	2.405	
T x H	1	0.246	
T x H within-group			
error	13	(0.001)	

\*\* $p < .001$

v. ANOVA Table for Transformed Efficiency Scores for Block 2 Female Participants,  
 Task x Hemisphere, Small Bin, High Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	113.312**	
Hemisphere (H)	1	0.089	
T x H	1	10.899*	
T x H within-group			
error	14	(0.001)	

\*\* $p < .001$

vi. ANOVA Table for Transformed Efficiency Scores for Block 2 Female Participants,  
 Task x Hemisphere, Small Bin, Low Frequency Conditions

Source	df	F	
		Efficiency Score	
Within subjects			
Task (T)	1	97.155**	
Hemisphere (H)	1	1.034	
T x H	1	0.095	
T x H within-group			
error	14	(0.001)	

\*\* $p < .001$

vii. ANOVA Table for Transformed Efficiency Scores for Block 2, Female Participants, Hemisphere (Task Consistent) x Condition (Hemispherically Consistent)

Source	df	F
		Efficiency Score
Within subjects		
Hemisphere (task consistent)(Htc)	1	335.105**
Condition (Hemispherically consistent)(Chc)	1	0.692
Htc x Chc	1	4.393*
Htc x Chc within-group error	14	(0.002)

\*\* $p < .001$

ix. Means and Standard Deviations for Each Variable for Block 2, Female Participants

---

Variable				
Task	Hemisphere	Bin	Frequency	<i>M</i> ( <i>SD</i> )
Metric	Right	Large	High	-0.784(0.098)
			Low	-0.774(0.094)
		Small	High	-0.780(0.124)
			Low	-0.787(0.143)
	Left	Large	High	-0.773(0.099)
			Low	-0.794(0.103)
		Small	High	-0.778(0.130)
			Low	-0.798(0.125)
Topological	Right	Large	High	-0.552(0.112)
			Low	-0.588(0.108)
		Small	High	-0.680(0.148)
			Low	-0.675(0.136)
	Left	Large	High	-0.549(0.104)
			Low	-0.590(0.128)
		Small	High	-0.616(0.140)
			Low	-0.674(0.167)

---