

© Copyright by Fahrettin Firat Gonen 2017

All Rights Reserved

**Real-Time Visual Stimulus Selection through Attentional and
Decisional Processes**

A Dissertation

Presented to

The Faculty of the Department of Electrical and Computer Engineering
University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

In Electrical and Computer Engineering

by

Fahrettin Firat Gonen

May 2017

Real-Time Visual Stimulus Selection through Attentional and Decisional Processes

Fahrettin Firat Gonen

Approved:

Chair of the Committee,
Haluk Ögmen, Professor,
Electrical and Computer Engineering

Committee Members:

Bruno G. Breitmeyer, Professor,
Psychology

Jose Luis Contreras - Vidal, Professor,
Electrical and Computer Engineering

Bhavin R. Sheth, Associate Professor,
Electrical and Computer Engineering

Vallabh E. Das, Professor,
College of Optometry

Suresh K. Khator, Associate Dean,
Cullen College of Engineering

Badri Roysam, Professor, Chair,
Electrical and Computer Engineering

Acknowledgements

I am grateful to my advisor, Professor Haluk Ögmen. I have been amazingly fortunate to have him as an advisor who gave me continuous support, guidance and endless patience throughout this journey. I feel very proud and lucky for his trust, to be part in his laboratory, and to be his graduate student. He was a true mentor not just for his scientific guidance but also for his excellence in ethics in every matter that he touched. His door was always open to me. I could not have imagined having a better advisor and a mentor for my Ph.D. study.

I am also very grateful for having an exceptional Ph.D. committee. I feel obliged for the invaluable supports and the insightful comments of Dr. Bruno G. Breitmeyer, Dr. Bhavin R. Sheth, Dr. Jose Luis Contreras – Vidal, and Dr. Vallabh E. Das.

I have also benefited from many discussions with members of our laboratory. I thank all my friends and colleagues for not just helping me designing experiments and technical assistance but also keeping the life in the laboratory more interesting. I would like to thank to all my friends for sparing their time and energy.

I am also indebted to my family: my wife Hazal, for her love and for her presence, my mother Bahar for her constant support, love and guidance, and my father Sait, for his generous support, love, and encouragement. I am grateful to all of them, for everything that I don't know how to express in words.

Dünyada herşey için; medeniyet için, hayat için, muvaffakiyet için en hakiki mürşit ilimdir, fendir. İlim ve fennin haricinde mürşit aramak gaflettir, dalalettir, cehalettir.

“Science is the most reliable guide for civilization, for life, for success in the world. Searching a guide other than science is meaning carelessness, ignorance and heresy.”

Gazi Mareşal Mustafa Kemal Atatürk

to

Mustafa Kemal Atatürk, Aziz Sancar, Haluk Öğmen, Sait Gönen

**Real-Time Visual Stimulus Selection through Attentional and
Decisional Processes**

An Abstract

of a

Dissertation

Presented to

The Faculty of the Department of Electrical and Computer Engineering

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

In Electrical and Computer Engineering

by

Fahrettin Firat Gonen

May 2017

Abstract

Our senses continuously receive a staggering amount of information from our environment. To operate efficiently in a natural environment, our brain needs to select in real-time a subset of the information impinging on our senses. Two processes play a crucial role in real-time stimulus selection and filtering: attentional and decisional processes. The broad goal of our study was to investigate how attentional and decisional processes select visual inputs for processing. The study was divided into three parts: The first and second parts studied visual attention. The last part examined decisional processes. In the first part, we investigated the allocation of exogenous attention when perceptual groups were formed or dissolved. By varying the relative timing between the cue onset and the formation, or dissolution of perceptual groups, we sought to understand the relationship between processes organizing inputs into meaningful units (perceptual grouping) and the processes selecting from these units (attention). The time-course of attentional benefits of grouping was remarkably similar in the case of group formation and dissolution, operating within a half-second time frame. The results revealed the dynamics of how attention and grouping work in synergy during the transient period when groups form or dissolve.

Attentional processes can be divided into two types: a fast reflexive process, called exogenous attention, and a slower, voluntary process, called endogenous attention. In the second part, we investigated whether endogenous and exogenous attention, operate independently or interact. The experiment demonstrated that there is an interaction between the endogenous and exogenous systems when the task was discrimination. The

evidence for interaction was weak when subject's task was detection. The interaction between the two orientation types depends on the validity of both types of orientations. When endogenous cue was valid, exogenous cue's strength was weakened. The endogenous cue was significantly dominant than the exogenous cue. The detection tasks required significantly less time compared to discrimination tasks.

In the last part, we examined information sampling by decisional processes. We tested the Small Sample Advantage (SSA) theory through predictions and found that for the low environmental contingency values, subjects preferred small sample sizes. For the remaining values, the prediction results were not conclusive. Under SSA, probability density function analysis indicates that the percentage correct can never exceed 50%. However, we carried out simulations to test whether the specific realization corresponding to our experiment could yield performance higher than 50% under SSA. Simulation results showed that indeed this was the case and produced an estimate of internal decision level used by the subjects.

Table of Contents

Acknowledgements	v
Abstract	ix
Table of Contents.....	xi
List of Figures	xv
List of Tables.....	xviii
Chapter 1. Introduction	1
1.1. Specific Aims	1
1.2. Significance and Innovation	2
1.3. Dissertation Outline.....	4
Chapter 2. Background.....	6
2.1. Visual Attention	6
2.1.1. Anatomy of the Human Visual System	7
2.1.2. Organization of the Human Visual Attention System	10
2.1.2.1. Posner’s Hypothesis.....	10
2.1.2.2. Caltech’s Hypothesis	11
2.1.2.3. Milanese Hypothesis	12
2.1.3. Mechanisms of Visual Attention	13
2.1.4. Endogenous vs. Exogenous Attention	14
2.1.5. Attentional Selection Theories.....	16

2.1.6. Object-based vs. Space-based Attention	17
2.1.7. Dynamic Stimuli	18
2.2. Perceptual Grouping and Organization	19
2.2.1. Gestalt Theory	19
2.3. Decision Making	22
2.3.1. Small Sample Advantage (SSA) Theory	23
Chapter 3. Exogenous Attention during Perceptual Group Formation and Dissolution	26
3.1. Introduction	26
3.2. Experiment 3.1: Exogenous Attention during Group Formation	29
3.2.1. Methods	30
3.2.1.1. Protocol and Subjects	30
3.2.1.2. Apparatus	30
3.2.1.3. Stimulus and Procedure	31
3.2.1.4. Results and Discussion	35
3.3. Experiment 3.2: Exogenous Attention during Group Dissolution	40
3.3.1. Methods	41
3.3.2. Results and Discussion	41
3.4. General Discussion	43
Chapter 4. Interactions between Endogenous and Exogenous Attention using Static and Dynamic Groups	47
4.1. Introduction	47

4.2. Experiment 4.1	51
4.2.1. Methods.....	51
4.2.1.1. Protocol and Subjects.....	51
4.2.1.2. Apparatus	52
4.2.1.3. Stimulus and Procedure	52
4.2.1.4. Results and Discussion	58
4.3. General Discussion	62
Chapter 5. Small Sample Advantage during Self-Guided Exploration.....	65
5.1. Introduction	65
5.2. Approach	66
5.3. Experiment 5.1 & 5.2: Homogeneous and Heterogeneous Displays	69
5.3.1.1. Protocol and Subjects.....	69
5.3.1.2. Apparatus	70
5.3.1.3. Predictions.....	70
5.4. Experiment 5.1: Homogeneous Displays	72
5.4.1. Procedure	73
5.4.2. Results and Discussion	76
5.5. Experiment 5.2: Heterogeneous Displays.....	82
5.5.1. Procedure	83
5.5.2. Results and Discussion	84
5.6. General Discussion	92
Chapter 6. Summary	94

6.1. Future Work	96
References	99
Appendix-A	121
Appendix-B	124

List of Figures

Fig 2.1. Spatial distribution of photoreceptors (rods and cones) in the retina (from Sekuler & Blake)	8
Fig 2.2. Where and What Pathways	9
Fig 2.3. Posner's hypothesis showing the three main regions involved with visual attention (from Posner and Peterson 1990).....	10
Fig 2.4. Caltech's hypothesis based on feature extraction at V1 level integrated with a Winner-Take-All network (from Koch, Ullman 1985).	11
Fig 2.5. Milanese feedback hypothesis (from Milanese 1993)	12
Fig 2.6: Flow Diagram of Feature Integration Theory.....	13
Fig. 2.7: Wertheimer's classical principles of grouping (from Palmer 1999).	22
Fig 3.1. The sequence of events when grouping starts 100 ms after the cue onset (i.e., Cue Onset Asynchrony with respect to Grouping, $COA_G = 100$ ms) (a), and when grouping starts 500 ms before the onset of the cue $COA_G = -500$ ms (b). Each trial started with a preview of 500 ms. Following the preview, the exogenous cue was presented for 100 ms. The cue onset asynchrony with respect to the target (COA_T) was set to 200 ms; i.e., the target was presented 200 ms after the onset of the cue. The target stayed on for 1000 ms or until the subject's response. Vertical red arrows indicate the initiation of grouping. As shown in the last frame, there were four different target options: the target could appear (i) in the cued disk (Valid), or (ii) in a non-cued disk that moves in the same direction as the cued disk (Invalid Within), or (iii) in a non-cued disk that moves in a different direction than the cued disk (Invalid Between), or (iv) at the spatial location where the cue appeared initially (Invalid Space).	33
Fig 3.2. A simplified overview of the relationship between the Cue Onset Asynchrony with respect to Grouping (COA_G) and the Cue Onset Asynchrony with respect to the Target (COA_T) for the 16 values of COA_G . Each box depicts the onsets of the cue and the target. COA_T was fixed at 200 ms to obtain a strong exogenous attention effect (Klein, 2000). The 16 COA_G values are represented in the timeline. When $COA_G = 0$, the onset of grouping occurs at the same time as the onset of the cue.....	34
Fig 3.3. Mean Reaction Times for all target options in Experiment 1 (formation of groups) as a function of Cue Onset Asynchrony with respect to Grouping (COA_G).	38
Fig 3.4. Mean Reaction-Time Difference ($\pm$ standard errors) for Invalid Within – Invalid Between Experiment 3.1 (formation of groups). The negative difference indicates attentional facilitation of grouping. For the group formation, the largest effect is present	

when COA_G is -500 ms. As the grouping time approaches (as the COA_G increases) to the cue presentation, the effect decreases..... 38

Fig 3.5. Mean Reaction Time Difference ($\pm$ standard errors) for Invalid Within – Invalid Between when COA_G is -600 ms, and -700 ms. For comparison, the data from Fig. 4 with $COA_G = -500$ ms is shown with the red circle. 40

Fig 3.6. Mean Reaction Times for all the target options in Experiment 2 (dissolution of groups) as a function of Cue Onset Asynchrony with respect to Grouping (COA_G). 42

Fig 3.7. Mean Reaction-Time Difference ($\pm$ standard errors) for Invalid Within – Invalid Between in Experiment 2 (dissolution of groups) as a function of COA_G . The negative difference indicates attentional facilitation of grouping. 44

Fig 3.8. Data from Figs 4 and 7 are plotted together to compare the time-course of attentional facilitation by grouping during the formation and the dissolution of groups. The dissolution data are flipped around the y-axis to take into account the fact that COA_G represents asynchrony with respect to the beginning and the end of the groups in Experiments 3.1 and 3.2, respectively. To reduce clutter, group formation and dissolution data are presented only with $-SEM$ and $+SEM$, respectively. 45

Fig 4.1. Stimulus configuration for Experiment 4.1 54

Fig 4.2. First Schematic Representation of the Exp 's stimuli (static case). When the endogenous cue is valid, exogenous cue can either be valid, invalid within (same color as the target but different one), or invalid between (other color with respect to the one, which cue is indicating). The trials start with a preview period of 500 ms. The preview is followed by the endogenous cue, which a central line showing one out of six squares. After the offset of the endogenous cue, ISI 1 comes (its duration is either 300 ms or 500 ms). ISI 1 is followed by the exogenous cue for 100 ms. The exogenous cue is an orientation change of one square. After ISI 2 of 100 ms, the subjects are required to make either detection or discrimination task while they see the target. For detection, the target is an X letter inside a square. For discrimination, the target is an arrow pointing to either right or left. The target stays on the screen for a maximum duration of 1000 ms..... 56

Fig 4.3. Second Schematic Representation of the Exp 's stimuli (static case). When the endogenous cue is invalid within (the endogenous cue points to a red square, the target will be inside another red square), exogenous cue can either be valid, invalid within, or invalid between. 57

Fig 4.4 Third Schematic Representation of the Exp 's stimuli (static case). Endogenous Cue is invalid between (endogenous cue is pointing the “other color” and not correct in terms of location). 58

Fig 4.5. Mean Reaction Times ($\pm$ standard errors) as a function of endogenous and exogenous cue validity. Detection conditions are significantly faster than discrimination conditions. In all conditions, valid/valid is the fastest compared to the rest..... 59

Fig 4.6. Mean Reaction Times ($\pm$ standard errors) as a function of endogenous and exogenous cue validity for different trial types..... 61

Fig 5.1. Sampling distributions comparing large and small samples for a positive Δ_s . Reproduced from Fiedler and Kareev (2006)..... 68

Fig 5.2. Probability density functions for Δ_s for different combinations of Δ_e and t . Assuming Δ_e is positive, Fig 5.1 A shows how the distributions of Δ_s would look like for large and small sizes. Both of them are centered at Δ_e and the small sample distribution is wider compared to large sample distribution. Hit and False Alarms correspond to the areas under $\Delta_s > t$ & $\Delta_s < -t$ respectively. Since $\Delta_e > 0$, and with more dispersion than large samples, small sample based decisions increased more hits than false alarms. In Fig 5.2 B, if $\Delta_s > t$, a decrease in hits is observed for small samples with a possible small increase in false alarms as well. Small sample advantage would only work if the threshold were higher than environment contingency meaning clear-cut evidence. The area under the curve from -1 to $-t$ is larger for small samples leading to more incorrect answers compared to large samples. Fig 5.2 C shows the case scenario, in which a high Δ_e is shown. Choosing a high relatively high t would slightly decrease the small sample advantage over large sample. Similar to Fig 5.2B, the area under the curve from -1 to $-t$ is larger for small samples leading to more incorrect answers compared to large samples. The Small sample advantage does not hold for high Δ_e values. Because Δ_e can't be more than 1, a narrower distribution would result in more advantage..... 74

Fig 5.4. N values for different Δ_e values for each set sizes. For SSA cases, larger Δ_e values give smaller N values as stated in Prediction 2. Error bars signify $\pm$ standard errors..... 79

Fig 5.5. Δ_s vs. Δ_e values for different set sizes. Δ_s increases as Δ_e increases. The average Δ_s is larger than Δ_e . Δ_s values don't differ for different set sizes, it is independent of set-size. Error bars signify $\pm$ standard errors. Black dashed line shows the hypothetical scenario when Δ_s is equal to Δ_e 80

Fig 5.6. Performance values for different Δ_e values for each set size, it is independent of set-size. Error bars signify $\pm$ standard errors. 81

List of Tables

Table 4.1	<i>All target options are listed below with their percentage occurrences.</i>	54
Table 4.2	<i>Paired sample t-test results for Experiment 2 showing significant test results when the endogenous cue is invalid for both static and dynamic stimuli</i>	62
Table 5.1	<i>2 X 2 contingency table</i>	67
Table 5.2	<i>From left to right: correct percentage, correct confidence level, incorrect percentage, incorrect confidence level, no choice percentage, sample size (N), Δ_s, and performance percentage (correct percentage – incorrect percentage) are reported for the homogeneous display.</i>	77
Table 5.3	<i>One-sample t-test results for each Δ_e values showing correlations between N and Δ_s as stated in Prediction 1. $M(r(\Delta_s, N))$ signifies the mean of the 15 Pearson Correlation values obtained from each subject's trial-by-trial data. $M(\Delta_s)$ signifies the sampled contingency mean for all the subjects; $M(N)$ signifies the mean of sample size for all the subjects. The last two rows in the table refer to statistic t and p (significance) in the t-test. All t-tests are based on $df=14$.</i>	78
Table 5.4	<i>Paired-sample t-test results comparing Δ_e and Δ_s values for Prediction 3. All t-tests are based on $df=2$.</i>	79
Table 5.5	<i>2 tailed t-test results for Δ_e values showing correlations between N and Confidence Ratings as stated in Prediction 4. $M(r(CR, N))$ signifies the mean of the 15 Pearson Correlation values obtained from each subject's trial-by-trial data. All t-tests are based on $df=14$.</i>	82
Table 5.6	<i>2 tailed t-test results for Δ_e values showing correlations between N and Performance as stated in Prediction 5. $M(r(P, N))$ signifies the mean of the 15 Pearson Correlation values obtained from each subject's trial-by-trial data. All t-tests are based on $df=14$.</i>	82
Table 5.7	<i>For each Δ_e value From left to right: correct percentage, correct confidence level, incorrect percentage, incorrect confidence level, no choice percentage, sample size (N), Δ_s, performance percentage (correct percentage – incorrect percentage), and subjects' choices for each set size in percentages are reported for the heterogeneous display.</i>	85

Table 5.8	<i>One-sample t-test results for each Δ_e values showing correlations between N and Δ_s as stated in Prediction 1. $M(r(\Delta_s, N))$ signifies the mean of the 15 Pearson Correlation values obtained from each subject's trial-by-trial data. $M(\Delta_s)$ signifies the sampled contingency mean for all the subjects; $M(N)$ signifies the mean of sample size for all the subjects. The last two rows in the table refer to statistic t and p (significance) in the t-test. All t-tests are based on $df=14$.</i>	85
Table 5.9	<i>Paired-sample t-test results comparing Δ_e and Δ_s values for Prediction 3. All t-tests are based on $df=14$.</i>	86
Table 5.10	<i>One-sample t-test results for Δ_e values showing correlations between N and Confidence Ratings as stated in Prediction 4 for the heterogeneous display. $M(r(CR, N))$ signifies the mean of the 15 Pearson Correlation values obtained from each subject's trial-by-trial data. All t-tests are based on $df=14$.</i>	87
Table 5.11	<i>One-sample t-test results for Δ_e values showing correlations between N and Performance as stated in Prediction 5. $M(r(P, N))$ signifies the mean of the 15 Pearson Correlation values obtained from each subject's trial-by-trial data. All t-tests are based on $df=14$.</i>	88
Table 5.12	<i>Simulation results for threshold values between 0.1 and 0.9 with a step size of 0.01. The complete table is at the Appendix A. The row with the yellow highlight shows t for which the error is minimum.</i>	91
Table 5.13	<i>Simulation results for threshold values between 0.3 and 0.5 with a step size of 0.001. The complete table is at the Appendix B. The row with the yellow highlight shows t for which the error is minimum.</i>	92
Table A.A-1	<i>Simulation results for threshold values between 0.1 and 0.9 with a step size of 0.01. The row with the yellow highlight shows t for which the error is minimum.</i>	121
Table A.B-1	<i>Simulation results for threshold values between 0.3 and 0.5 with a step size of 0.001. The row with the yellow highlight shows t for which the error is minimum.</i>	124

Chapter 1. Introduction

1.1. Specific Aims

Under natural viewing conditions, our eyes receive a staggering amount of information; therefore we need a real-time selection mechanism to be able to operate in real-time. Visual attention is a key stimulus selection process. The main goal of our study was to investigate how attentional and decisional process select visual inputs for further processing. One way to reduce stimulus complexity is to organize the stimulus into meaningful units, known as Gestalt grouping. In our previous study, we investigated how exogenous attention is deployed to stimuli that form distinct meaningful entities (perceptual groups). We showed that exogenous attention is deployed according to a reference frame that moves along with the stimulus. Moreover, in addition to the cued element of the group, exogenous attention was deployed to all elements forming a perceptual group. In our first experiment set, we investigated the allocation of exogenous attention when perceptual groups were formed and dissolved. We varied the relative timing between the onset of the cue and the formation, or dissolution of the groups. In the second part of the study, we examined whether endogenous and exogenous attentions operated independently or interacted during stimulus selection. Our last study was related to how humans make decisions and how decision processes sampled information before making a decision. To summarize our objectives, we condensed our studies in 3 specific aims:

***Specific Aim 1:** to investigate the dynamics of how attention is allocated to perceptual groups. In particular, to understand how attentional allocation takes place during the formation and dissolution of perceptual groups.*

***Specific Aim 2:** to investigate whether exogenous and endogenous attention operate independently or through interactions.*

***Specific Aim 3:** to test the hypothesis that small samples lead to better decisions than large samples for detecting stimulus contingencies during self-guided exploration.*

1.2. Significance and Innovation

The amount of information coming to our senses and especially to our eyes is staggering. Our nervous system is required to select a subset of the received data and discard the rest of information. Without filtering what is irrelevant, or without prioritizing the information, a real-time analysis of the environment would be impossible. Understanding how these selection mechanisms operate is crucial in our understanding of how the nervous system functions in a natural environment. Our nervous system carries out these functions through attentional and decisional processes. There are many studies concerning visual attention, its orienting types, its different coordinates, and their interactions. However, most of these studies used static stimuli in investigating fundamental properties of attention. On the other hand, our natural environment is dynamic and moving objects often carry a high degree of behavioral relevance. A second shortcoming of existing studies is their use of relatively simple stimuli. Gestalt psychologists have shown that perceptual grouping, i.e., the organization of stimuli into

meaningful units, is a fundamental aspect of visual processing. In fact, by joining related parts of the stimuli into a single entity, perceptual grouping plays an essential role in reducing the complexity of the stimuli. Hence, it was essential to understand how attention and perceptual grouping reduce *jointly* the complexity of stimuli making real-time perception possible. Thus, an innovation of our study was to study jointly two fundamental processes of stimulus complexity reduction.

Another important gap in our knowledge of how the brain selects information was the lack of understanding whether the two components of attention, exogenous and endogenous attention, operate independently in parallel or through interactions. The current findings in the literature are limited and contradictory. We modified our stimulus to investigate whether endogenous and exogenous attention interact for static as well as moving stimuli.

Moreover, very little is known on how humans sample their environment to make decisions. Law of large numbers and common sense suggest that large samples are preferable over small samples but how humans choose sample size is not well understood. The small sample advantage theory provides a solid mathematical basis for the interpretation of how humans examine their surroundings, and makes their decisions. The innovation and the significance of the study were to provide a mathematical foundation for an approach where small samples are favorable over large samples.

The broader significance of this work can be described from three perspectives. First, a better understanding of human attentional and decisional processes can lead to a better understanding of their dysfunctions as in diseases like Alzheimer's disease or Attention Deficit Hyperactivity Disorder. Alzheimer's disease and ADHD are known to

cause many attentional problems during their early epochs (Corbetta & Shulman 2002; Danckert et al 1998; Dodd & Pratt 2005; Hopfinger & West 2006; Snyder et al 2007; Renner et al 2006). Second, understanding how humans make decisions can have a significant impact in social and economical sciences. Finally, the availability of massive data and computing power placed neural network learning systems among the best machine learning approaches. However, it is well recognized that a major shortcoming of these approaches is their inability to operate autonomously in natural environments and actually select inputs upon which they can build their knowledge. Hence, a front-end to interface these systems to natural environments is lacking. The research in this dissertation addressed the key processes of such a front-end.

1.3. Dissertation Outline

The dissertation consisted of 7 chapters. The remaining chapters are outlined as follows:

- Chapter 2 gives background information about visual attention, perceptual grouping, and decision-making.

- Chapter 3 describes the 1st study, which examined the exogenous attention during perceptual group formation and dissolution.

- Chapter 4 presents the 2nd study, which explored the interactions between endogenous and exogenous attention using static and dynamic groups.

-Chapter 5 reports the 3rd and the last study, which examined the small-sample advantage during self-guided exploration.

-Chapter 6 gave the general discussion and future works for the whole dissertation combining all the three studies conducted.

Chapter 2. Background

2.1. Visual Attention

In very short words, visual attention guides us decide where our eyes should move next. But before discussing more thoroughly, let's give some quotes by the pioneers:

Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought (James, 1890).

People talk about attention with great familiarity and confidence. They speak of it as something whose existence is a brute fact of their daily experience and therefore something about which they know a great deal, with no debt to attention researchers (Pashler, 1998).

Attention is the allocation of the limited cognitive resources in order to process information in real-time. Due to several factors, there have been significant advances on our understanding of visual attention in the past 30 years. Systematical characterization of the distinct attentional systems and their perceptual effects by psychophysical researchers, single-unit primate neurophysiological studies, neuro-imaging studies (functional magnetic resonance imaging fMRI, event-related potentials ERP, steady-state visual evoked potentials SSVEP, magneto encephalography MEG), eye-tracking technology developments, and computational modeling can be considered as the main significant advances in the visual attention field.

2.1.1. Anatomy of the Human Visual System

This section gives only an overview of the anatomy of the human visual system in order to understand why we need visual attention. The retina collects the visually received information and it is transferred to two distinct brain regions (the lateral geniculate nucleus, LGN; and the superior colliculus, SC). The transfer is made possible by the optic nerve. Two pathways make possible the transfers. The retino-geniculate pathway is responsible for about 90% of the visual information to the visual cortex and it covers both the spatial and temporal information. Collicular pathway, on the other hand carries important data for visual attention and eye movements.

The retina is located inside the back lining of the eye and contains photosensitive cells. The retina cells are classified into two categories: rods and cones. Fig 2.1 shows the distribution of rods and cones in the retina. There are 5×10^6 cones inside the retina and they are responsible for color vision. As seen on the figures, cones are not uniformly distributed in the retina. On the other hand, there are only 10^8 rods in the retina, and they are responsible for night vision. Rods are highly concentrated on the central part of the retina called fovea. Through both sides of eccentricity, cone concentration decreases. The photoreceptors are connected to the ganglion cells through bipolar cells. We can classify ganglion cells into three categories: M (Magno) ganglion cells, P (Parvo) ganglion cells, and a third category for neither M nor P ganglion cells. P ganglion cells are usually associated with central vision; they are connected to the cone cells located in the fovea. On the other hand M ganglion cells are connected to the cone cells located in the periphery. Beside their location differences, they are different in terms of spatial and temporal resolution. P ganglion cells have smaller receptive fields compared to M

ganglion cells, creating a higher spatial resolution. M ganglion cells have better temporal resolution (Boucart et al., 1998).

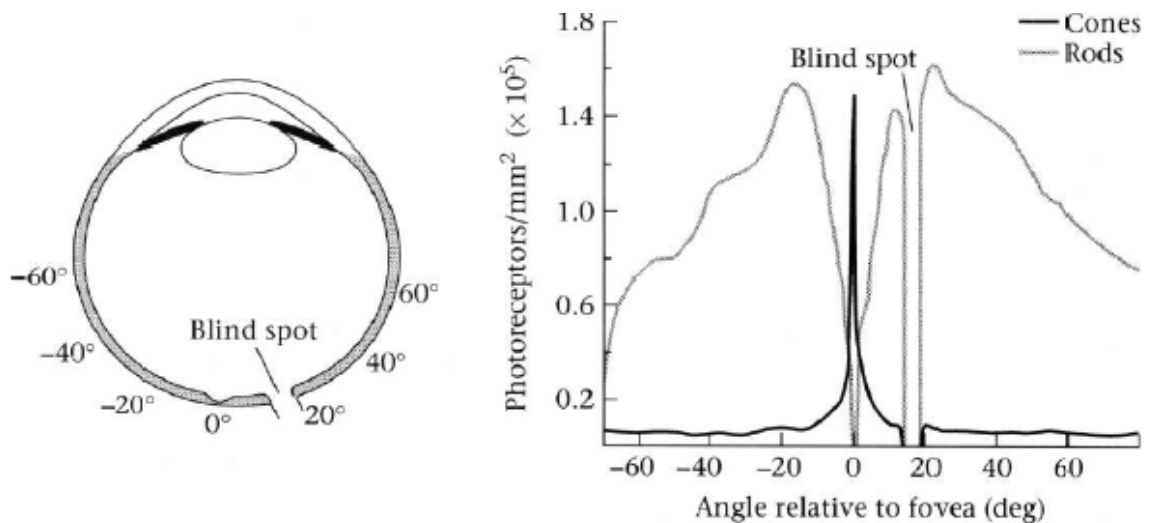


Fig 2.1. Spatial distribution of photoreceptors (rods and cones) in the retina (from Sekuler & Blake)

The thalamus is located in the dorsal and anterior region of the brain and contains the lateral geniculate nucleus (LGN), the pulvinar nucleus, and the reticulate nucleus (RN). The main role for the lateral geniculate nucleus is to feed the visual information to the cerebral cortex. Three different types of cells form the LGN: parvocellular, magnocellular, and koniocellular. The parvocellular and magnocellular cells are the preceding cell modules respectively for P and M ganglion cells located inside the retina. They feed two different visual information streams (Levine, 1985). The third and last type of the ganglion cells corresponds to the koniocellular cells of the lateral geniculate nucleus. The other part of the thalamus is the reticular nucleus and it influences the attentional mechanisms (Milanese 1993, Bollmann 1999). This region can be considered like an alert mechanism to increase the speed and effectiveness of the visual attention system.

There are approximately 10^{10} cells inside the visual cortex. The area V1, also

called the primary visual cortex or striate cortex can be considered as a “hub” of the hierarchy due to the fact that V1 represents the main gate for the visual information received from lateral geniculate nucleus. 50% of the information received at V1 comes from the fovea. The visual information is then transmitted to V2. After V2, information is feed to two different pathways: the parvocellular stream goes to V4 whereas the magnocellular goes to V3 and V5 (MT: middle temporal area). As seen in Fig 2.2, until V2 both pathways (where and what) have common regions. V4 is usually associated with color and form. Inferior temporal cortex (IT) is responsible for object recognition. That’s the reason this stream is also known as the “what” pathway. V5 is responsible for dynamic object localization, motion answering the question of “where”. Where pathway plays an important role for visual attention deployment (Itti & Koch 2001). We can easily characterize these findings not just to humans but also to primates as well.

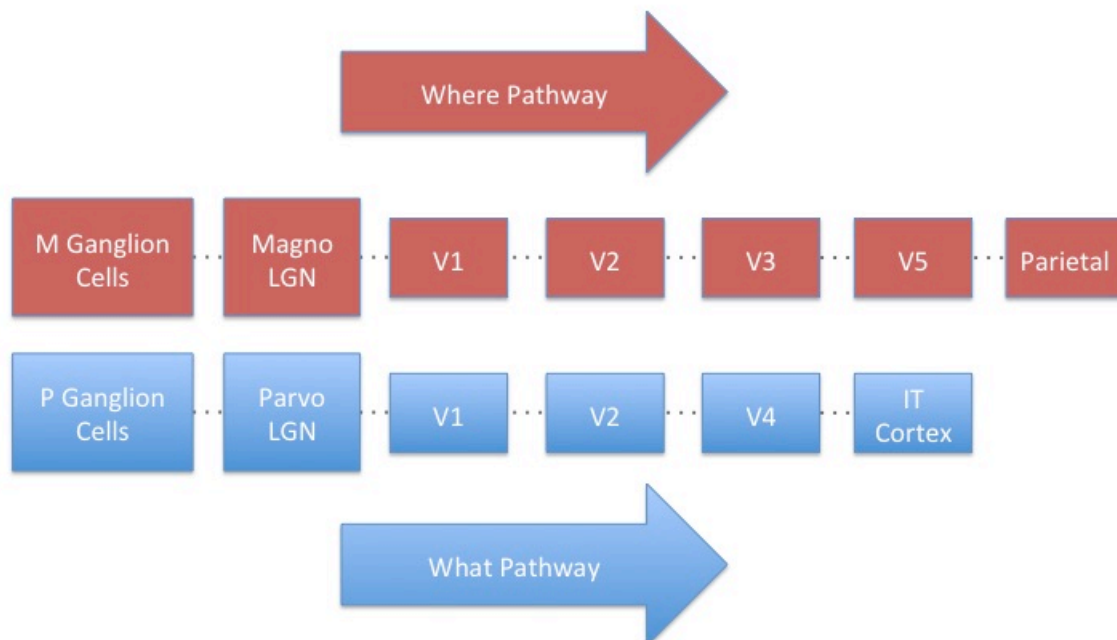


Fig 2.2. *Where and What Pathways*

2.1.2. Organization of the Human Visual Attention System

Even though we showed the responsibilities of several brain regions in the visual system, their clear definition does not exist. Still, we learned much more knowledge about human visual attention through functional Magnetic Resonance Imaging (fMRI) and through several patients. There are three main hypotheses for the organization of the human visual attention system and they are all scattered over several brain areas.

2.1.2.1. Posner's Hypothesis

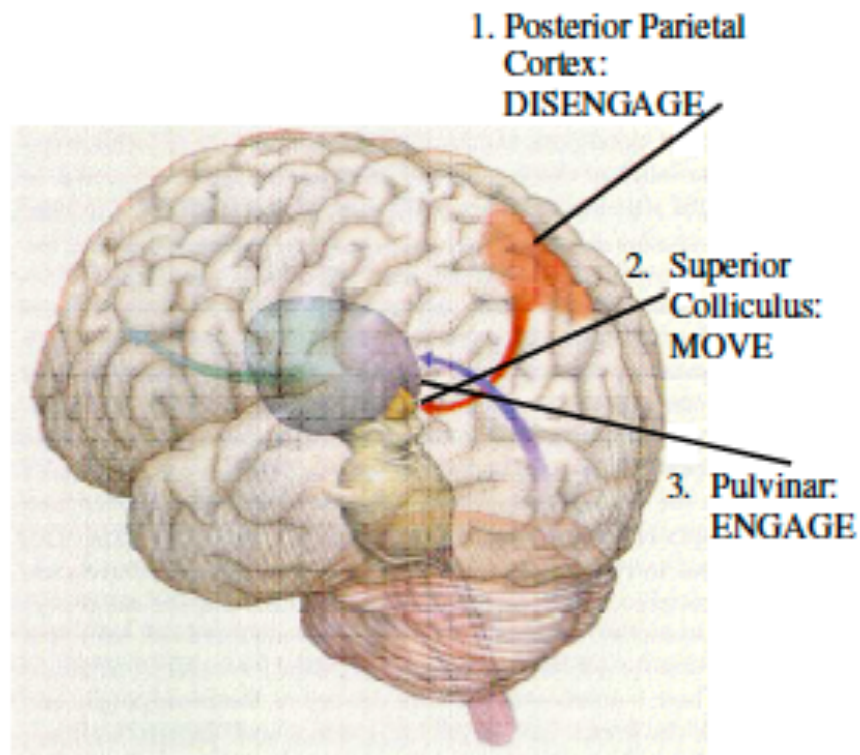


Fig 2.3. Posner's hypothesis showing the three main regions involved with visual attention (from Posner and Peterson 1990).

Posner's hypothesis consists of three main categories (Posner, Peterson 1990): first, the attentional focus needs to disengage from its original location needs to shift and last it needs to re-engage to a new location. As seen from Fig 2.3, the Posterior Parietal made the disengagement possible while the Superior Colliculus was responsible from the shifting process. The engagement was made possible the pulvinar area.

2.1.2.2. Caltech's Hypothesis

The hypothesis was first created by Koch and Ullman (Koch, Ullman 1985) and then developed by Niebur (Niebur & Koch 1996 & 1998). According to the hypothesis, basic features are drawn at V1, motion at MT, and color at V4. These features form a saliency map residing at LGN. After everything, Winner-Take-All network detects the most salient scene location.

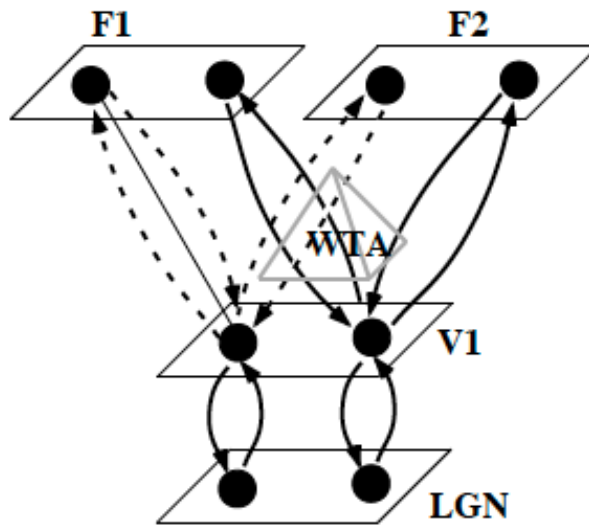


Fig 2.4. Caltech's hypothesis based on feature extraction at V1 level integrated with a Winner-Take-All network (from Koch, Ullman 1985).

2.1.2.3. Milanese Hypothesis

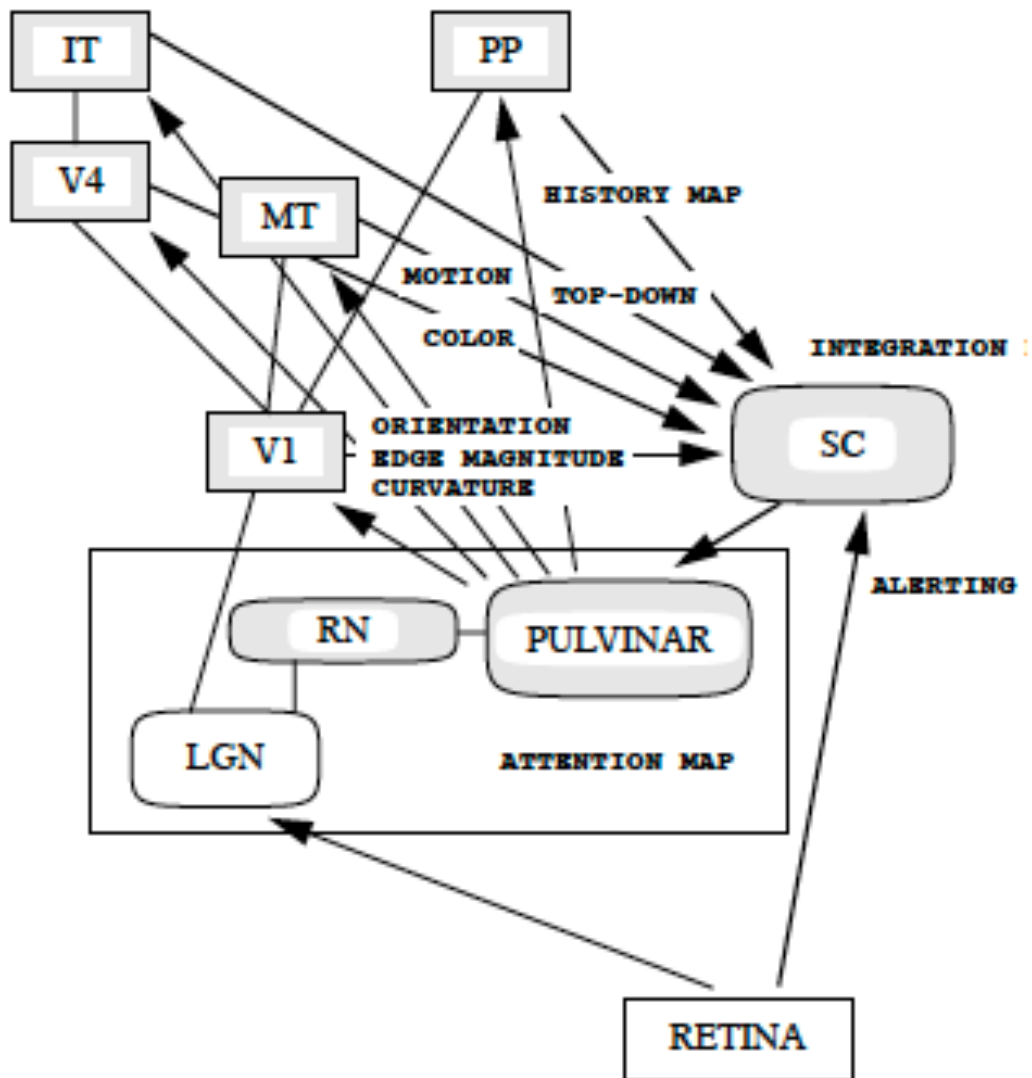


Fig 2.5. Milanese feedback hypothesis (from Milanese 1993)

Milanese extended Caltech's hypothesis by combining it with the work of Posner (Posner, Peterson 1990) and of Desimone (Desimone et al., 1990). The result was more detailed description. Similar to Koch, it suggests several cortical areas being responsible

for features. The integration process was made by superior colliculus. The thalamus was responsible for a final map of visual attention.

2.1.3. Mechanisms of Visual Attention

There are three main mechanisms of visual attention to describe in this section: selectivity, capacity limitation and sense of exertion. To study selectivity, visual search and Feature Integration Theory need to be studied (Treisman & Gelade, 1980). Treisman and colleagues presented a paradigm, in which the subject was shown both target and distractor stimuli. They varied the display size (number of stimuli) for each trial. The task was to decide whether the target was present in that trial or not as fast and accurate as possible. The duration of the decision was graphed as a function of display size to show the distractor effects. The proposed work by Treisman and Gelade was two different modes of visual search: parallel and serial modes. According to their theory, search rate, which was the slope of the graph mentioned above, was an indicator for whether the subject used parallel or serial search. Increased slope would mean parallel processing. On the other hand, if the function resulted with a linear increase, the search would be assumed to be serial (Muller & Krummenacher, 2006). Fig 2.6 briefly describes the two-staged flow diagram of Feature Integration Theory.

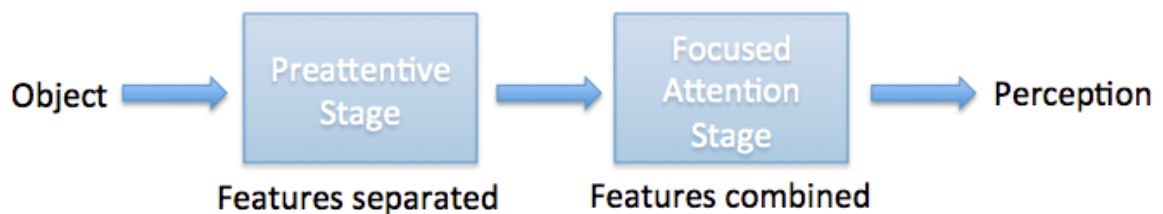


Fig 2.6: Flow Diagram of Feature Integration Theory

Selective attention is how we filter the irrelevant and focus on “what really matters”. Another mechanism beside selectivity of the visual attention is the capacity limitation, which limits the parallel visual search ability discussed in the above paragraph. The capacity becomes important when dealing with visual short-term memory (VSTM). VSTM have role in perceptual and cognitive functions, is supported by several brain regions, but it's capacity is strictly limited. A classic paradigm to experiment VSTM is to display several different colored disks and after giving some time (retention period) to the subjects, with the help of a probe, the task is usually to decide whether the probed disk matches to the one of the previous disks as in location and/or in color (Todd & Marois, 2004).

The last mechanism in this section is the effort (sense of exertion) due to visual attention. It is known that when a location or an object is allocated, the efficiency of the process around it increases. Attention can be allocated voluntary (endogenous control) or automatically, (exogenous control). Although different mechanisms create these two different brain activities, the neural map for both types of attentional control is believed to be overlapping (Rosen et al., 1999; Gonen et al., 2016). Next section will give more details about the two types of attentional orienting.

2.1.4. Endogenous vs. Exogenous Attention

Generally, attentional orienting is divided into two main categories: endogenous attention and exogenous attention (Posner, 1980; Jonides, 1981; Weichselgartner & Sperling, 1987; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Cheal & Lyon,

1991; Egeth & Yantis, 1997; Carrasco 2011; Boi et al., 2011). Endogenous (top-down) attention is slow, allocated by voluntary control to a stimulus (e.g. an object) or location. Exogenous (bottom-up) is the fast, involuntary, reflexive component of the visual attention. It is relatively faster compared to endogenous attention. The general paradigm to examine endogenous and exogenous attention is Posner's double cueing paradigm (Posner, 1980; Posner & Cohen, 1984, Moore et al., 1998), in which a target is preceded by a peripheral or a central cue. The endogenous attention is allocated by a central cue (e.g., an arrow) marking the possible location of the target depending on its validity percentage. A central cue is generally presented in the center of the screen, usually at the same location of subject's focus of attention. It generally (but not necessarily) allocates endogenous attention. A peripheral cue is very brief abrupt, generally presented outside of the focus of attention. It mainly allocates exogenous attention. Generally stimuli presented at the cued locations require less time to detect compared with the uncued locations, leading to a conclusion that the endogenous attention shifted to the cued location. In the exogenous processing, instead of a central cue, an abrupt onset cue is presented at one of the target locations. The cue, having an abrupt onset creates an automatic allocation for the attention. As in the endogenous attention, the cued locations require less time to detect compared with the uncued locations. From the memory point-of-view, the memory load can disrupt endogenous attention performance, whereas exogenous attention is independent from the memory load (Chica et al., 2006; Chica et al., 2013). Exogenous and endogenous attention differ both qualitatively and quantitatively. Exogenous attention's effect is more seen at early stages of processing. It affects the stimulus enhancement, external noise reduction, and perceptual processing in

object-based coordinates. On the other hand, endogenous type of orienting works at late stages of processing (Chica et al., 2007; Chen et al., 2012; Chica et al., 2013). Even though the two mechanisms are considered to be independent, several studies concluded that they interact (Busse et al., 2008; Chica et al., 2008; Chica et al., 2013; Posner et al., 1985; Jonides et al., 1981; Chen et al., 2012; Grubb et al., 2015). Generally when the task includes discrimination, instead of detection: endogenous attention usually increases the effect of exogenous attention (Chica et al., 2013). Considering the previous studies, we reach the conclusion that there are two different neural substrates having common regions to create the noted interaction above. The two neural circuits responsible for endogenous and exogenous attention are only partially segregated. The literature is not in line with the point-of-view that both endogenous attention and exogenous attention use two different limited-capacity pools interacting each other.

2.1.5. Attentional Selection Theories

Several attentional selection theories use the example of a bottleneck restricting the rate of the flow. Narrower the bottleneck, the rate of flow would decrease. Even though almost all of them use the “bottleneck principle”, they differ in many aspects. Our study focus is not on different types of attentional selection theories, though we will provide only brief information on the most main ones. They all agreed that extensive filtering was a necessity due to limited pool of resources. The main point where they all disagreed was the place of the filtering. Broadbent (1958) defended an early-filter processing based on physical attributes such as location. According to Broadbent, unattended information was not even processed beyond its location. An alternative to

Broadbent's theory was more of a late-processing mechanism suggested by Deutsch & Deutsch (1963) and by Duncan (1984), these studies defended the view that selection mechanism was efficient after the categorization of the inputs. A third category is the intermediate view by Treisman (1960). According to her, the unattended information is also processed but not the same degree as the prior information.

As said, our study focus was not selection theories. For further information about this topic, Pashler's (1998) extensive review of the literature is suggested.

2.1.6. Object-based vs. Space-based Attention

The traditional view is that visual attention has two coordinates: space-based and object-based attention (Abrams & Law, 2000; Duncan, 1984; Egly, Driver, & Rafal, 1994; Egly, Driver, Rafal, & Starrveveld, 1994; Iani, Nicoletti, Rubichi, & Umiltà, 2001; Lamy & Egeth, 2002; Reppa 2012; Soto & Blanco 2004; Theeuwes et al. 2013; Ro & Rafal 1999). In space-based coordinates, visual attention is allocated to locations. Evidence for space-based attention comes from cuing tasks, allocating visual attention to a region. Spotlight (Eriksen & Eriksen, 1974; Eriksen & Hoffman, 1973; Hoffman & Nelson, 1981; Posner, 1980; Posner, Snyder, & Davidson, 1980), or zoom lens (Eriksen & St James, 1986; Eriksen & Yeh, 1985) metaphors are used to describe space-based attention. The evidence obtained from visual cuing experiments shows that attention needs more time for allocation as the distance between the cue and the target increases (Lamy & Tsal 2000; Shulman et al., 1979; Tsal, 1983; Brown et al., 2006). In object-based coordinates, attention is directed to an item or multiple items indicating a group of

items coherently linked to each other. The definition of the object concept is still ambiguous among attention researchers (e.g., Humphreys & Riddoch 2003; Kasai, Moriya, & Hirano 2011; Marr 1982; Pinna 2014; Scholl 2001; Vecera 1994; Vecera & Farah 1994; Prinzmetal 1981). The object concept was defined in many different ways. We believe that the concept of objects can be explained by the use of perceptual groups.

2.1.7. Dynamic Stimuli

One of the main challenges in object-based attention studies is the problem of differentiating the object cueing effects vs. the effects coming from their locations if the paradigm is dynamic instead of static. The solution to this problem is to cue both the object and the location within different trials. This method would allow the object effects being separated from its location-based (spatial) effects. If the visual system works only location-based, then the movement based effects will not be present. However, if it were the other way around, then the benefits would be still present. This technique was generally used for Inhibition of Return studies (Abrams & Dobkin, 1994; Behrmann & Tipper, 1999; Christ et al., 2002; Gibson & Egeth, 1994; Kahneman et al., 1992; Lamy & Tsal, 2000; McCrae & Abrams, 2001; Müller & von Mühlenen, 1996; Ro & Rafal, 1999; Soto & Blanco, 2004; Tipper & Behrmann, 1996; Tipper et al., 1991; Tipper, Jordan, & Weaver, 1999; Tipper et al., 1994; Umiltà et al., 1995; Vivas, Humphreys, & Fuentes, 2008; Weaver, Lupiáñez, & Watson, 1998). This technique was also used to find the facilitatory effects (Lamy & Tsal, 2000; Soto & Blanco, 2004, Ro & Rafal, 1999, Gonen et al., 2014). Attentional effects for dynamic stimuli were present as well. In their stimuli, comparing the distance to understand the location-based effects of cuing; the distance

between the cue and the cued object was less short than the distance between the cue and the uncued object. In these studies, the results showed the potential additional influence of the spatial effects to the objects effects observed. In Ro & Rafal's (1999) work, spatial effects were compared to equidistant within-object and between-objects effects, and the facilitatory effects from exogenous cues were observed.

2.2. Perceptual Grouping and Organization

Perception is the received, filtered, processed information from all senses. The sensory inputs are crucial to perceive the environment around us. In order to create a complete representation, sound, touch, body balance, taste, acceleration but also visual perception is required. We can generally categorize visual perceptual operations into two: bottom-up (data-driven) and top-down processes. Bottom-up processes start from retina and go to visual cortex. Through the process, each region is responsible for a more complex process compared to the previous region. On the other hand, top-down processes depending on prior knowledge and past experience, the complete stimuli are used to understand the smaller parts.

2.2.1. Gestalt Theory

Christian von Ehrenfels first introduced Gestalt concept. The roots of it go to the theories of David Hume, Immanuel Kant, Johan Wolfgang von Goethe, David Hartley, and Ernst Mach. After the introduction of Gestalt concept, Max Wertheimer firstly introduced the Gestalt psychology. According to Gestalt approach, the brain is seen as a

whole and analog in a holistic approach. The mechanisms are considered as non-linear. Kurt Koffka in his famous quote: “*The whole is greater than the sum of its parts*” describes the theory. In German, the word (Gestalt) means shape or form. The main difference between the behaviorists and Gestaltists is that behaviorists try to understand the brain in a modular way. On the other hand, Gestaltists are interested in the general organization of the whole brain. Koffka, Wertheimer, and Köhler, when analyzing perception, they put into account the whole background, and environment for a better holistic picture. This holistic approach created the global principles of perception. Even though Gestalt is a globally accepted theory, there are critics suggesting that the theory is only descriptive. Prägnanz, which is the indispensable principle of the Gestalt laws of grouping, is the concept of categorizing our experience in a regular, simple, symmetrical manner. There are several Gestalt examples; some of them are very famous like the waterfall illusion or the rabbit-duck illusion. Another one is the Kanizsa triangle, which seems to be a triangle, no existence in reality. The brain tends to complete these images to give a meaning.

We can organize the principles of grouping or “Gestalt laws of grouping” into 7 main categories: proximity, similarity, closure, symmetry, good continuation (continuity), common fate, and good form (good Gestalt). Over the time several categories were introduced as additional categories.

Proximity: This principle states that, if all the remaining features are equal, the perception tend to group the stimuli being closer than the rest.

- **Similarity:** In this principle, if the seen stimuli resemble each other; the perception tends to group that part as same objects (groups), and vice versa holds as well.

- **Closure:** In this principle, the mind tries to complete the objects that it processes, even though it's incomplete, obscured, partially hidden. With this ability to complete things by filling in, we have less missing information. The closure principle has also survival role in hunting and escaping in the nature.
- **Symmetry:** This organization principle states that the mind always tries to categorize the visible stimuli into symmetrical even groups.
- **Continuity:** This principle, also called “good continuation” creates a differentiation when there is a visual overlap on the allocated object or space. Lines or curves that follow abrupt changes are organized and grouped in a way that would make meanings.
- **Common Fate:** this principle suggests that if the visual stimuli move in the same direction, they are all considered as a single group. A flock of birds is the perfect example for the common fate condition. Hundreds of birds are perceived as a unified whole group.
- **Good Form:** This phenomena making the environment's perception more simple, eliminates the complexity and the irregular patterns. This principle is also called “the law of Prägnanz”.

(Gonen, Master of Science thesis, 2013).

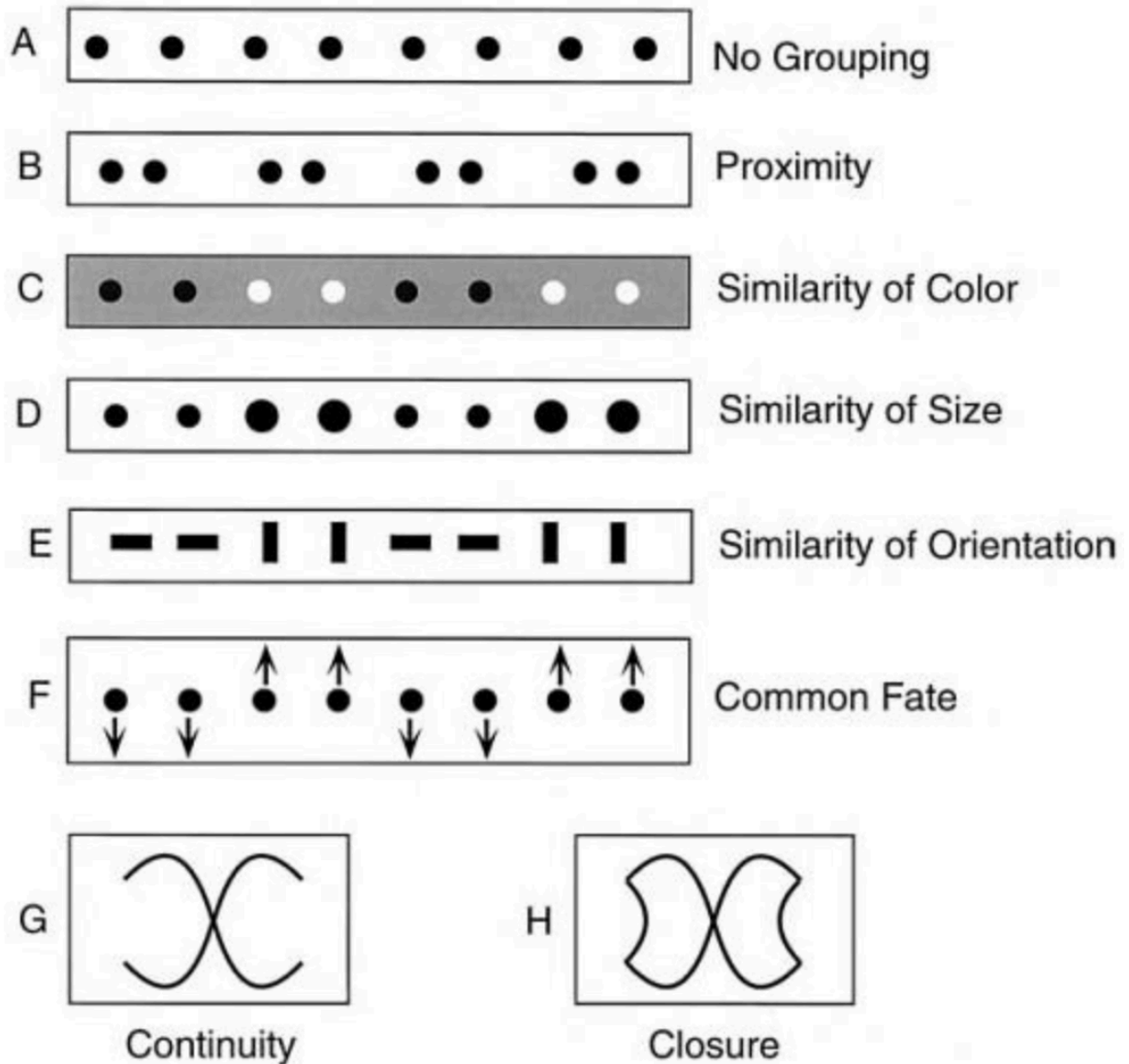


Fig. 2.7: Wertheimer's classical principles of grouping (from Palmer 1999).

2.3. Decision Making

In psychology, decision-making is considered as a cognitive process. It usually results with a selection of action or no action among the present possibilities. Each decision-making creates a final product but it doesn't have to cause action. Decision-making is a two-step process, in which first, the identification and then second the choice

between the alternatives based on the parameters and preferences. Over the years, decision-making topic became interesting and challenging for neuroscientists and cognitive scientists. fMRI studies showed that several brain regions including the anterior cingulate cortex (ACC), orbitofrontal cortex and ventromedial prefrontal cortex are involved in process (Walton et al., 2004). Damasio and Antonio (1994) found that patients having damage to the ventromedial prefrontal cortex have challenges when making decisions. When designing a paradigm to study decision-making, usually 2AFC (two-alternative forced choice task) is used within a certain time period. A 2AFC decision-making study on rhesus monkeys concluded that parietal cortex is not just responsible to make a decision but also the degree of certitude (confidence) for that decision (Gold et al., 2007; Kiani et al., 2009). Kennerley et al. (2006) found that lesions at anterior cingulate cortex in the macaque monkey caused an impaired decision-making.

2.3.1. Small Sample Advantage (SSA) Theory

In cognitive research, the information gathered, the amount of it, if taken as a function, cannot take any negative values. Similar to economist approach, as in money or power, the value of the information increases monotonically with its amount (Fiedler & Kareev, 2006). The typical form of a monotonically increasing, negatively accelerated learning curve shows that gain from a high number of trials (or practices) may become zero at the asymptote but it never loses of its value (for a no-loss system). This theory asks this challenging question of whether smaller samples can lead to better decisions when compared to large decisions. A study revealed that retail customers are more satisfied with their purchases when their decisions are based on quick “gut” decisions

(Wilson & Schooler, 1991). Several studies confirmed that increasing the amount of information could lead to performance drops even though measured performance was independent from fatigue or overload (Borges, Goldstein, Ortman, & Gigerenzer, 1999; Elman, 1993; Gigerenzer & Goldstein, 1996; Hertwig & Todd, 2003; Krauss & Wang, 2003; Martignon & Hoffrage, 1999; Newport, 1988, 1990). Bernoulli's law of large numbers is usually taken granted when it comes to decisions based on contingent event. Kareev (Kareev, 1995, 2000; Lieberman & Lev, 1997) found that contingencies could be decided better with small samples under some conditions (boundary conditions).

Fiedler and Kareev (2006) observed small sample advantage over large samples using a satisficing-choice framework under clear, specific boundary conditions. They analyzed accuracy and confidence of the decisions as a function of sample size. In a nutshell, their vital assumption was that subject could only decide and produce a choice only if the sample exceeded a clear-cut decision threshold. Otherwise no choice would be possible, and additional information was not received.

In Fiedler and Kareev's study, (2006) a proof of the small samples outperforming large samples was provided investigating the quality of decisions based on a contingent binary choice. The paradigm was composed of 2 X 2 contingencies between two options focusing on the sample size and the quality of the choice (More information about their framework and theoretical base is available in the 5th chapter of the dissertation). According to the authors, the subjects implement a threshold-based decision mechanism regarding their output. A decision can be made only if the contingency of the sampled environment passes the pre-determined threshold meaning that the subjects decide with the help of a "clear-cut picture of evidence before they make a choice".

Fiedler and Kareev (2006) conducted two empirical experiments to search for the small sample advantage. In the first experiment, they asked the subjects to decide between two potential job-candidates relying on sampled evidence (positive or negative) until subjects were satisfied enough to stop. They discovered negative correlations between sample size and performance. They also found negative correlations between sample contingency and sample size. In their second experiment, subjects were given fixed sample size and they scored better for small samples in specific trials. The chosen trials were the ones with specific decision thresholds.

One of the many critics regarding their research is that the sample contingency is usually on the extreme for small than large samples because of the fact that small samples doesn't represent the rare events (Evans & Buehner, 2011; Hertwig & Pleskac, 2008). Several studies criticized small sample advantage theory claiming that it is against human behavior due to the fact that the theory-model is independent of several factors such as fatigue, overload, or noise. Griffin and Tversky (1992) suggested that humans seem to adapt dynamic (lowering) thresholds. Cahan (2006) in his commentary argues that small sample advantage is not intuitive and its focus can only be for binary choice scenarios. Cahan argues that small sample advantage does not contradict law of large numbers. He describes the small sample advantage as an application to estimate, while concluding Fiedler and Kareev's work as "false alarm".

Chapter 3. Exogenous Attention during Perceptual Group Formation and Dissolution

3.1. Introduction

Under natural viewing conditions, a large amount of information reaches our senses and the brain uses visual processes to reduce the complexity of the stimuli in order to operate in real-time. One of the complexity reduction processes is attention, which can prioritize and/or filter select parts of the stimuli for further processing. Another process of complexity reduction is perceptual grouping, which consists of clustering together stimuli according to certain regularities that generally indicate a common origin (Wagemans et al., 2012; Wertheimer, 1923). Instead of processing every pixel in an image as an independent input, perceptual grouping allows the processing of millions of pixels united into wholes (e.g., a face). Given that both attention and perceptual grouping play a major role in stimulus complexity reduction, it is important to understand how they work together to make real-time perception possible.

Visual attention has two modes of orienting (e.g., Cheal & Lyon, 1991; Egeth & Yantis, 1997; Jonides, 1981; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Posner, 1980; Posner & Cohen, 1984; Weichselgartner & Sperling, 1987; Nakayama & Mackeben, 1989; Gonen et al., 2014; Carrasco 2011; Boi et al., 2011): Endogenous attention is under voluntary control and can be allocated flexibly to stimuli based on task demands. Hence, stimulus complexity reduction by endogenous attention takes place on a voluntary and task-dependent fashion. For example, when searching for a red object, endogenous attention can be deployed to enhance the processing of red stimuli while

suppressing the rest of the stimuli. On the other hand, exogenous attention is involuntary and constitutes a reflexive response to the stimulus itself. Because it lacks the flexibility inherent to the endogenous attention, a question arises as to *which aspects* of a stimulus does the exogenous attention become allocated.

Several studies reported that, similar to endogenous attention, exogenous attention too can be allocated to retinotopic and spatiotopic locations as well as to “objects” (e.g., Boi, Vergeer, Ogmen, & Herzog, 2011; Brown, Breitmeyer, Leighty, & Denney, 2006; Egly, Driver, & Rafal, 1994; Egly, Rafal, Driver, & Starrveveld, 1994; Iani, Nicoletti, Rubichi, & Umiltà, 2001; Lamy & Egeth, 2002; Lamy & Tsal, 2000; Moore, Yantis, & Vaughan, 1998; Reppa, Schmidt, & Leek, 2012; Theeuwes, Mathôt, & Grainger, 2013; Vecera, 1994). However, what defines an “object” remains an ill-posed problem (e.g., Humphreys & Riddoch, 2007; Kasai, Moriya, & Hirano, 2011; Marr, 1982; Pinna, 2014; Scholl, 2001). Contour closure is often used as an important property of objects and explanations of how attention spreads from the location of the cue to the entire object may be based on a process that is limited by the closed contours of the object (e.g., Carey & Xu, 2001; Scholl & Leslie, 1999). However, “object”-based attentional benefits have been reported for stimuli with open contours (e.g., Avrahami, 1999; Marino & Scholl, 2005; Marrara & Moore, 2003), for gestalt groups without contours (Marrara & Moore, 2003) as well as for spatio-temporal gestalt grouping relations (Boi et al., 2011; Gonen et al., 2014).

These findings suggest an important role for perceptual grouping in the allocation of exogenous attention; it directs exogenous attention to simpler and behaviorally meaningful wholes rather than an indiscriminate spread over the complex stimulus.

Recent studies also showed a more nuanced concept of “object” from *perceptual* object to *semantic* object (Li & Logan, 2009; Yuan & Fu, 2014) or to a *higher-level* of object (Zhao et al., 2014). Li and Logan showed that forming a compound word is much more efficient in terms of attentional shift when compared to a non-word (Li & Logan, 2009). Yuan and Fu demonstrated that relation-based knowledge could also link objects to form perceptual-based groups similar to Gestalt principles (Yuan & Fu, 2014). Zhao and colleagues studied the object representation strength by comparing the top-down objects to bottom-up objects, they found that the attention would be allocated to the higher strength object (Zhao et al., 2014).

In our previous study, in which we investigated the joint operation of exogenous attention and perceptual grouping (Gonen et al., 2014), we used the grouping principle of “common fate” to form distinct groups of moving disks and showed that when a cue was presented in one of the disks, it facilitated responses not only for the cued moving disk but also for other disks that shared the same direction of motion as the cued disk (Gonen et al. 2014). In other words, exogenous attention was allocated to the entire perceptual group formed by the principle of common fate. The common fate principle is known to affect perceptual organization and hence attentional allocation using perceptual objects (Kahneman & Henik, 1981; Tipper et al., 1990; Watson & Kramer, 1999). Kahneman and Henik argued that pre-attentive processes are responsible for early perceptual units or perceptual objects. After the pre-attentive processes, by the allocation of attention, the process of analyzing all the properties of the perceptual object is done (Kahneman & Henik, 1981). Tipper, Brehaut, and Driver found that distractors moving with the same speed as the targets create more inhibitory performance compared to static distractors

because of the common fate principle (Tipper et al., 1990). Watson and Kramer, in their “wrench-shaped object” study, demonstrated that the perceptual groups or objects don’t have to be single-regioned as long as all the regions inside the perceptual group (or object) are task relevant (Watson & Kramer, 1999).

In Gonen et al. (2014), a stable perceptual group was already established at the time the cue appeared. In a natural environment, groups can be dynamically formed and dissolved. For example, a herd of animals may initiate a coordinated movement pattern; as an animal in camouflage starts to move, movements of different body parts can dynamically form a perceptual group; similarly when the herd disperses or the animal stops the dynamic perceptual group dissolves.

In many survival situations, it is important to detect and allocate attention to such dynamic groups as soon as possible. Similarly, as a dynamic group dissolves, it is important to be able to maintain the identity of the group as long as possible. The goal of the current study was to investigate how exogenous attention is allocated *during the formation* and *during the dissolution* of perceptual groups. To achieve this goal, we conducted two experiments: one with the formation and the second with the dissolution of perceptual groups.

3.2. Experiment 3.1: Exogenous Attention during Group Formation

The goal of the first experiment was to investigate the allocation of exogenous attention during the *formation* of perceptual groups.

3.2.1. Methods

In this section, the respected protocol, the apparatus used and the procedure in designing the experiment are discussed.

3.2.1.1. Protocol and Subjects

All experiments reported in this study were conducted in accordance with the federal regulations, 45 CFR 46, the ethical principles established by the Belmont Report, and the principles expressed in the Declaration of Helsinki, according to a protocol approved by the University of Houston Committee for the Protection of Human Subjects. Twelve University of Houston students participated in each experiment. All subjects had either normal or corrected-to-normal vision. With the exception of the first author who served as subject, all subjects were naïve to the purpose of the experiments. Subjects' participation was voluntary and they gave their written informed consent according to a protocol approved by the University of Houston Committee for the Protection of Human Subjects.

3.2.1.2. Apparatus

The stimuli were presented on a 20-inch NANA O FlexScan color monitor in a dark room. The resolution of the display was 656 X 492 pixels with a 100 Hz frame rate. A video card (Visual Stimulus Generator; VSG 2/3) manufactured by Cambridge Research Systems was used for stimulus generation. A head-and-chin-rest was fixed at a distance of 1 meter from the display monitor. The screen size was approximately 23° X

17.5° and one pixel corresponded to 1.7 arcmin. A joystick interfaced to the VSG board was used to measure reaction times.

3.2.1.3. Stimulus and Procedure

Fig. 3.1 shows a schematic depiction of the stimulus. The stimulus consisted of six disks. Each disk had a diameter of 0.8° visual angle. The fixation point was a white plus sign (+) placed in the center of the monitor. Each disk moved along a linear trajectory with a speed of 5 deg/s. When the paths of different disks crossed, they continued their independent linear trajectories by passing across each other. The initial positions of the disks were selected inside a virtual circle centered on the fixation point and of diameter 5° so that the disks would never reach the edge of the screen. The CIE 1931 XYZ space was used. The colors for all the disks were blue with a luminance of 4 cd/m² (CIE XYZ coordinates: 0.3044, 0.6541, 4). The background was black. The cue and the target appeared on top of one disk, and had smaller diameters (0.6° visual angle) than the disks. Their CIE color coordinates were 0.2044, 0.48085 corresponding to white color with a luminance value of 20 cd/m². The task of the subject, while fixing his/her eyes to the fixation cross, was to press a joystick button *as soon as* the target appeared. At the beginning of each trial, six disks, with randomly chosen six starting positions (inside the aforementioned virtual circle), started to move along linear trajectories, with each direction of motion selected randomly. Prior to grouping, each disk moved with a randomly selected direction of motion with the constraint that they were 20 degrees apart from each other in order for them not to form a prior perceptual group.. At the start of the grouping, half of the disks moved with a common randomly selected direction, whereas

the other half moved with a common randomly selected direction. The two directions of motion were selected randomly with the constraint that they were at least 30 degrees apart from each other in order to have a salient difference between the two groups. After the initial preview period of 500 ms, the cue appeared in one of the randomly selected disk and traveled along with this disk for 100 ms and disappeared at the end of the 100ms. A target was presented in one of the disks 100 ms after the disappearance of the cue. The target also traveled with the disk. Catch trials were included, in which no target appeared and the subjects had to abstain from pressing the joystick button. Any incorrect responses on catch trials were indicated to the subject by audio feedback. The maximum duration of the target was set to 1000 ms, during which the subject had to press the joystick button.

The experiment had a total of 16 different values of the independent variable, which was the start of grouping with respect to the onset of the exogenous cue (Cue Onset Asynchrony with respect to Grouping, COA_G). Fig 2 shows the relationship between the Cue Onset Asynchrony with respect to the Target (COA_T), which was fixed at 200 ms to obtain a strong exogenous attention effect (Klein, 2000), and COA_G for each of the 16 values of COA_G . Each red box in this figure represents a different case in terms of COA_G . In the 1st case, COA_G was set to -500 ms (the earliest moment possible), thus grouping started from the very beginning, so COA_G was -500ms.

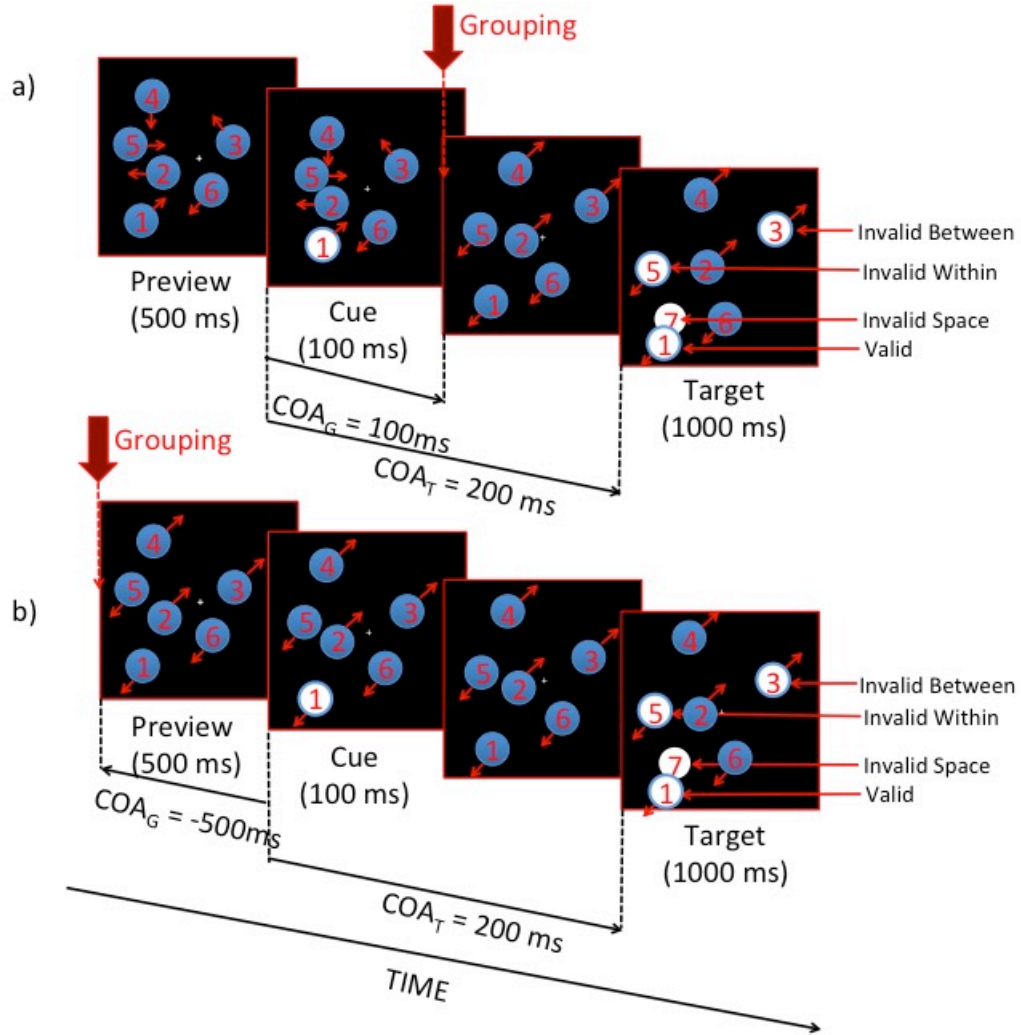


Fig 3.1. The sequence of events when grouping starts 100 ms after the cue onset (i.e., Cue Onset Asynchrony with respect to Grouping, $COA_G = 100 \text{ ms}$) (a), and when grouping starts 500 ms before the onset of the cue $COA_G = -500 \text{ ms}$ (b). Each trial started with a preview of 500 ms. Following the preview, the exogenous cue was presented for 100 ms. The cue onset asynchrony with respect to the target (COA_T) was set to 200 ms; i.e., the target was presented 200 ms after the onset of the cue. The target stayed on for 1000 ms or until the subject's response. Vertical red arrows indicate the initiation of grouping. As shown in the last frame, there were four different target options: the target could appear (i) in the cued disk (Valid), or (ii) in a non-cued disk that moves in the same direction as the cued disk (Invalid Within), or (iii) in a non-cued disk that moves in a different direction than the cued disk (Invalid Between), or (iv) at the spatial location where the cue appeared initially (Invalid Space).

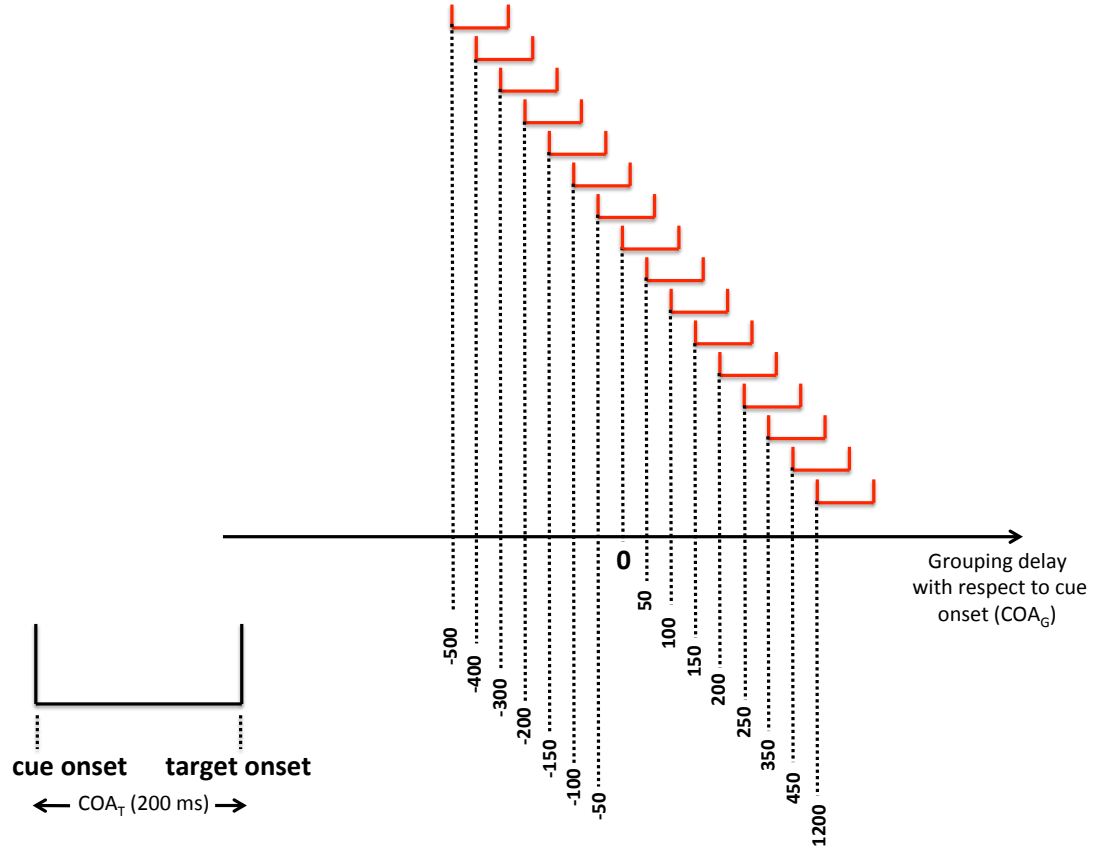


Fig 3.2. A simplified overview of the relationship between the Cue Onset Asynchrony with respect to Grouping (COA_G) and the Cue Onset Asynchrony with respect to the Target (COA_T) for the 16 values of COA_G . Each box depicts the onsets of the cue and the target. COA_T was fixed at 200 ms to obtain a strong exogenous attention effect (Klein, 2000). The 16 COA_G values are represented in the timeline. When $COA_G = 0$, the onset of grouping occurs at the same time as the onset of the cue.

This case was identical to the experiments in Gonen et al. (2014). Motion trajectories during the entire trial consisted of two linear randomly chosen trajectories. The case where the COA_G was 0 refers to the case in which grouping and the onset of the cue happened at the same time. In the case where the COA_G was 1200, there was no grouping, since 1200 ms corresponded to the end of the target presentation. As shown in Fig. 2, the values for COA_G were -500, -400, -300, -200, -150, -100, -50, 0, 50, 100, 150, 200, 250, 350, 450, and 1200. The “Valid” target appeared in the same disk as the cue.

The “**Invalid Within**” target appeared in a disk that belonged to the same perceptual group as the cued disk (i.e., a disk that moved along the same motion direction as the cued disk). “**Invalid Between**” target appeared in a disk that did not belong to the same group as the cued disk (i.e., a disk that moved along a different direction of motion than the cued disk). Another target option was “**Invalid Space**”, in which, the target did not appear in any disk, but its appearance was in the original retinotopic/spatiotopic location of the cue. This target option was valid from a space-based point of view. In order to remove any distance-based effect between invalid-within and invalid-between conditions, the average distance (calculated over all trials) between the cue and the invalid-within condition was set equal to the average distance between the cue and the invalid-between condition. The cue’s average eccentricity was kept balanced by making the average eccentricity of the cue equal across blocks. The average eccentricity was 3.5°. To keep the eccentricity of the target the same between invalid-between and invalid-within conditions, the average distance between the invalid-within and the fixation point was set equal with the average distance between the invalid-between and the fixation. The presentation of all target options was randomized within each block. Each block had 48 trials for each target option (catch trials were also considered as one of the five target options) yielding 240 trials per block. Four sessions per subject yielded 960 trials with an additional 300 training trials.

3.2.1.4. Results and Discussion

Reaction times (RTs) less than 150 ms and greater than 1000 ms were excluded from all analyses. These exclusions constituted 1.8% of all data. Accuracy in catch trials

was higher than 95% for all subjects. RT data were analyzed by one-way repeated measures ANOVA. Fig. 3 shows the raw data for each target type. In general RTs ranged from 240 ms to 290 ms, in accordance with RTs found in simple detection tasks (Gonen et al., 2014; Abrams & Law, 2000; List & Robertson, 2007; Jordan & Tipper, 1999; Marino & Scholl, 2005; Posner, 1980; Ro & Rafal, 1999). The effect of COA_G was significant [$F(1, 15) = 8.611$, $p < .001$, $\eta_p^2 = .365$] and in general large COA_G values yielded faster RTs. One exception was the Invalid Space case at COA_G = 0 ms, which yielded a relatively high RT. When COA_G = 0 ms, the cue appears at the same time when the disks change their direction of motion to initiate the two groups. Since, changes in the direction of motion is a very salient event itself, the occurrence of this salient event at the time of the appearance of the cue may reduce the effectiveness of the cue, hence leading to an increased RT. However, it is not clear why this would happen only in the Invalid Space case and not in the others. A possible explanation is that the change of motion direction may guide attention towards the disks and away from the original spatial location of the cue. If this speculation were true, one would then expect all three target options, with the exception of Invalid Space, to still benefit from attentional resources. For many COA_G values, Invalid Space generated fastest RTs, indicating the presence of space-based attention; however, space-based attention did not produce fastest RTs consistently for all COA_Gs.

In order to examine object-based attentional facilitation, we show in Fig 4 the mean RT difference between Invalid-Within and Invalid-Between conditions. As seen from Fig. 4, when grouping happens early enough (when COA_G values are negative enough, e.g. -500, -400 and -300) the RT difference is negative indicating a clear

attentional facilitation. The overall effect of COA_G on RT difference is significant [$F(1, 15) = 3.675$, $p < .01$, $\eta_p^2 = .962$]. In order to determine which RT differences (Invalid within – Invalid between) were significantly different from zero, we ran a t-test for all data points in Fig. 4. The Bonferroni-corrected confidence interval was adjusted from 0.05 to 0.003125. All RT differences for negative COA_G values from -500 ms to -50 ms were significantly different from zero (for COA_G = -500, $t(11)=3.956$, $p=0.002$, $d=0.605$, for COA_G = -400, $t(11)=3.314$, $p=0.003$, $d=0.216$, for COA_G = -300, $t(11)=2.114$, $p=0.0029$, $d=0.197$, for COA_G = -200, $t(11)=2.427$, $p=0.002$, $d=0.321$, for COA_G = -150, $t(11)=4.432$, $p=0.0013$, $d=0.754$, for COA_G = -50, $t(11)=3.221$, $p=0.0031$, $d=0.124$). The most negative value of COA_G corresponds to the case where grouping starts from the beginning, as in our previous study (Gonen et al., 2014). In both studies, we found a strong attentional facilitation for the entire group. We also observe here that the attentional facilitation becomes weaker when the timing of the initiation of the group becomes closer to the timing of the cue.

Hence, in terms of formation of groups, the results indicate that the effect of grouping is gradual and builds up within the interval of 500 ms examined in this experiment. In addition to grouping-based comparisons of attentional effects, we also compared the RT of the Valid target option to the Invalid Within option in order to assess space-based attentional effects. We found a significant space-based attentional effect ($F(1, 15) = 14.972$, $p = .002$, $\eta_p^2 = .5$).

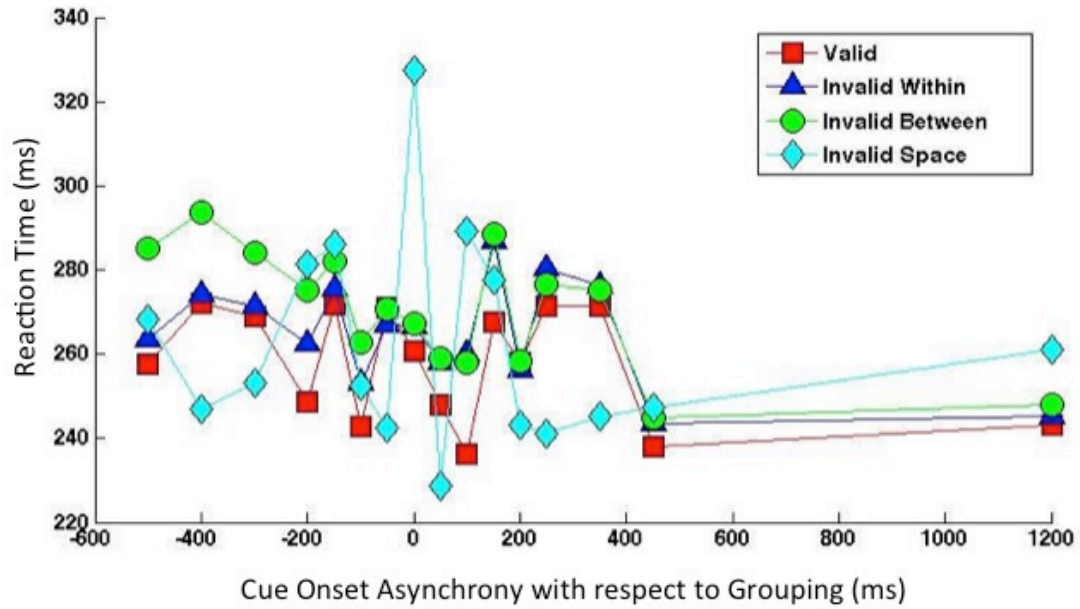


Fig 3.3. Mean Reaction Times for all target options in Experiment 1 (formation of groups) as a function of Cue Onset Asynchrony with respect to Grouping (COA_G).

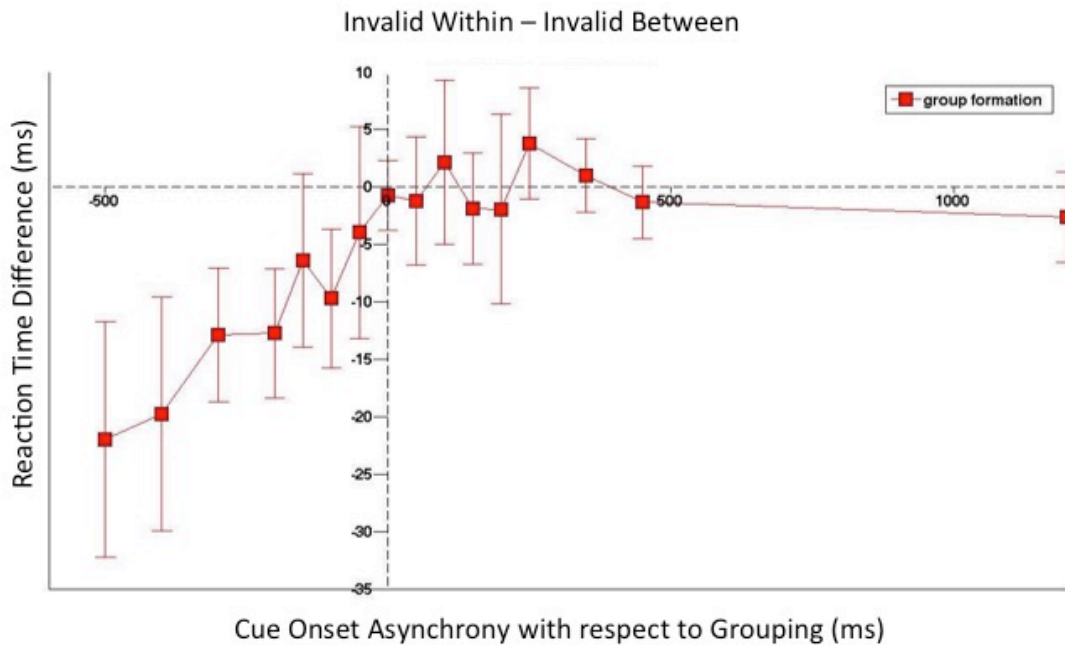


Fig 3.4. Mean Reaction-Time Difference ($\pm$ standard errors) for Invalid Within – Invalid Between Experiment 3.1 (formation of groups). The negative difference indicates attentional facilitation of grouping. For the group formation, the largest effect is present when COA_G is -500 ms. As the grouping time approaches (as the COA_G increases) to the cue presentation, the effect decreases.

In the data of Fig. 3.4, there is no apparent saturation in the benefits of attentional effects since the RT differences seem to follow a linear decrease as COA_G becomes more and more negative. In order to investigate whether there is a critical duration of group formation after which the attentional effect becomes saturated, we collected additional data, in which we had COA_G values of -600 and -700 with 12 subjects (all University of Houston graduate students, age average: 28, min age 26, max age 31, only four of the subjects were new subjects). The trials consisted of only the Invalid Within and the Invalid Between trials presented in random order. Each block had 120 trials for each target option including 24 catch trials (20%). Four sessions per subject yielded 1440 trials with an additional 300 training trials. The results are plotted in Fig. 5. For comparison, the $COA_G=-500$ ms data point from fig. 4 is also included (circle). Paired t-test between RT differences at $COA_G = -700$ ms and -600ms resulted with a non significant effect ($t(11)=2.1745$, $p=0.1934$, $d=1.71$). Considering the data point from Fig. 4 also, one can see that the effect saturated beyond $COA_G=-500$ ms.

Taken together, the results of these experiments show that the effectiveness by which exogenous attention allocates resources to perceptual groups depend on the temporal history of group formation. It is a relatively slow process building up within few hundred milliseconds and leveling to a steady state in half a second.

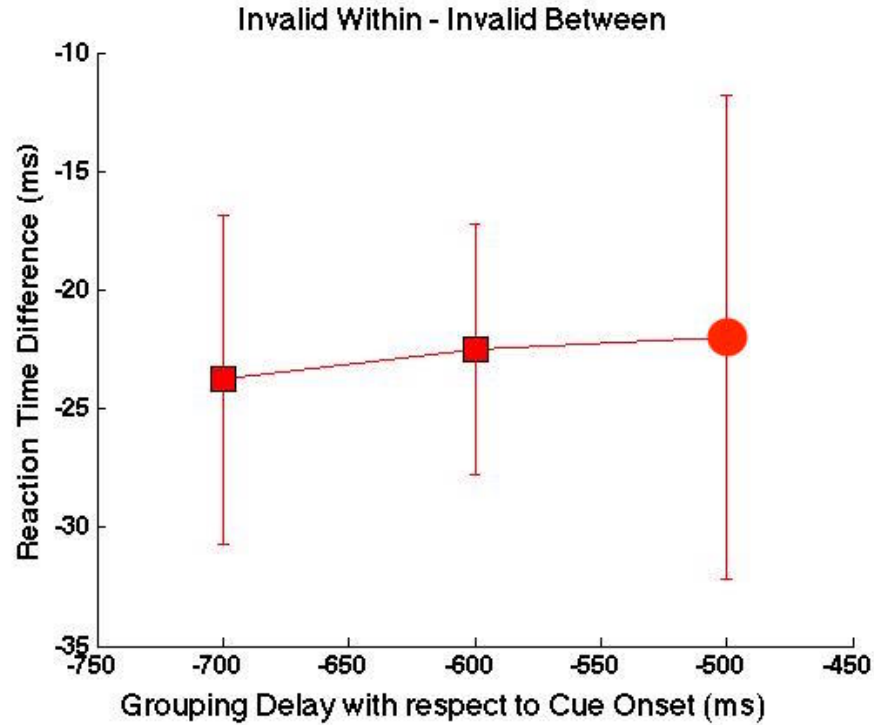


Fig 3.5. Mean Reaction Time Difference ($\pm$ standard errors) for Invalid Within – Invalid Between when COA_G is -600 ms, and -700 ms. For comparison, the data from Fig. 4 with $COA_G = -500$ ms is shown with the red circle.

3.3. Experiment 3.2: Exogenous Attention during Group Dissolution

The goal of the second experiment was to determine the allocation of exogenous attention during the *dissolution* of perceptual groups. As in Experiment 1, we used the common fate principle and varied the relative timing between the appearance of the cue and the dissolution of perceptual groups. Similar to Experiment 1, we separated objects into two distinct groups by their direction of motion. Each COA_G value represented a different delay compared to the onset of the exogenous cue but this time representing the *dissolution* of the already established perceptual group.

3.3.1. Methods

The methods were same as in Experiment 1 with the following exception. The 16 different COA_G values represent the onset time of the cue with respect to the onset of the dissolution of the group. E.g.: If the COA_G is -300, with the start of the preview (see Fig. 3.1), the disks start their motion already grouped into two, and after 200 ms (300 ms prior to the exogenous cue), the two groups dissolve resulting with six disks having 6 different random (linear) trajectories.

3.3.2. Results and Discussion

Reaction times less than 150 ms and greater than 1000 ms were excluded from all analysis constituting 1.4% of all data. Accuracy in catch trials was higher than % 96. RT data were analyzed by one-way repeated measures ANOVA. Fig. 3.6 shows the raw data for each target type. The effect of COA_G was significant [$F(1, 15) = 34.079$, $p < .001$, $\eta_p^2 = .694$]. RTs start at 280 ms to 300 ms range, close to the ones observed in Experiment 1, but become gradually larger as COA_G increases. Invalid Space condition tends to produce fastest RTs especially for negative values of COA_G, indicating the presence of space-based exogenous attention.

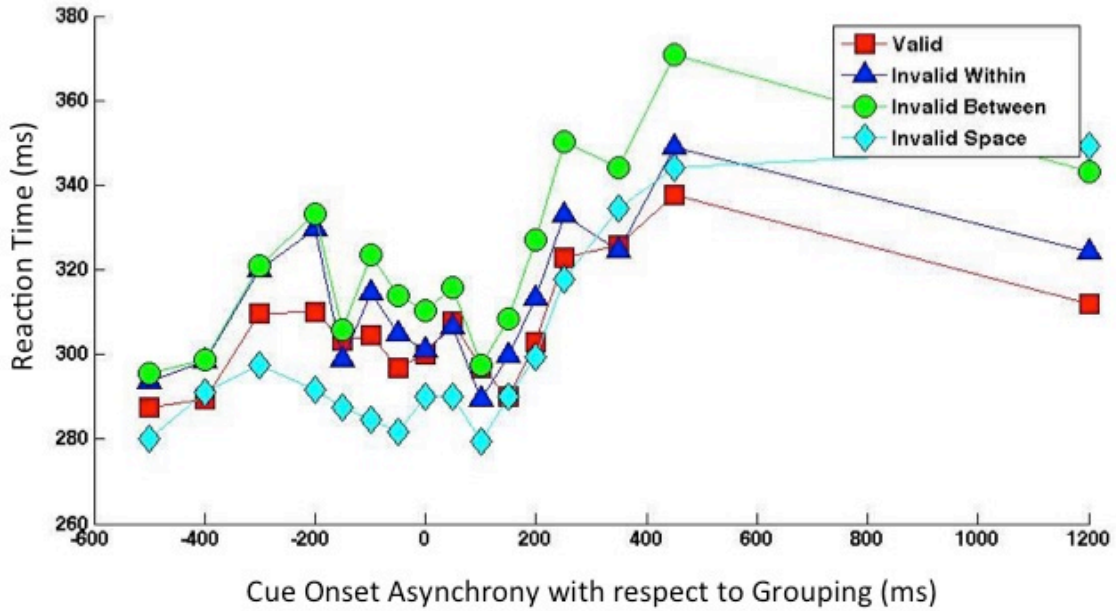


Fig 3.6. Mean Reaction Times for all the target options in Experiment 2 (dissolution of groups) as a function of Cue Onset Asynchrony with respect to Grouping (COA_G).

Fig 3.7 shows the mean RT difference between Invalid Within and Invalid Between conditions. The effect of COA_G on RT difference is significant [$F(1, 15) = 18.642$, $p < .005$, $\eta_p^2 = .209$], and negative RT difference values indicate a clear attentional facilitation. In order to determine which RT differences (Invalid within – Invalid between) were significantly different from zero, we ran a t-test for all data points in Fig. 7. The Bonferroni-corrected confidence-interval was adjusted from 0.05 to 0.003125. For COA_G values equal to 1200, 450, 350, 250, 150, 100, 50, 0, -50, -100, the the RT differences were significantly different than zero (for $COA_G = 1200$, $t(11)=3.475$, $p=0.001$, $d=0.051$, for $COA_G = 450$, $t(11)=3.124$, $p=0.001$, $d=0.017$, for $COA_G = 350$, $t(11)=2.994$, $p=0.0021$, $d=0.265$, for $COA_G = 250$, $t(11)=4.616$, $p=0.003$, $d=0.62$, for $COA_G = 150$, $t(11)=3.921$, $p=0.0021$, $d=0.654$, for $COA_G = 100$, $t(11)=4.541$, $p=0.003$,

$d=1.23$, for $COA_G = 50$, $t(11)=2.113$, $p=0.001$, $d=0.852$, for $COA_G = 0$, $t(11)=0.741$, $p=0.003$, $d=0.795$, for $COA_G = -50$, $t(11)=4.328$, $p<0.001$, $d=0.991$, for $COA_G = -100$, $t(11)=2.634$, $p=0.001$, $d=1.14$). Note that here COA_G represents the time at which grouping dissolves with respect to the onset of the cue. Negative and positive COA_G values indicate that grouping dissolved before and after, respectively, the presentation of the cue. As expected, attentional benefits of grouping occurs strongly for positive values of COA_G and decays as COA_G becomes negative. Attentional benefits for negative values of COA_G show that the attentional benefits of grouping persist for some time after the dissolution of the groups. As in the Exp 1, in order to see the effect of space-based attention, we compared the RT of the Valid target option to the Invalid Within option. Overall, the COA_G effect on space-based attention was significant ($F(1, 15) = 12.944$, $p = .003$, $\eta_p^2 = .463$).

3.4. General Discussion

Stimuli impinging on the retina are very complex and the real-time vision necessitates the reduction of this complexity. Attention and perceptual grouping are two processes involved in complexity reduction. There have been extensive investigations on how each of these processes in isolation can reduce stimulus complexity. Starting with the rejection of the atomistic view, Gestalt theory introduced a variety of perceptual grouping principles that lead to a more wholistic, simplified, and behaviorally relevant representations of the environment (rev., Koffka, 1935; Wagemans et al., 2012). Research on attention identified “space-based” as well as “object-based” processes (Egley et al., 1994a; Egeth & Yantis, 1997).

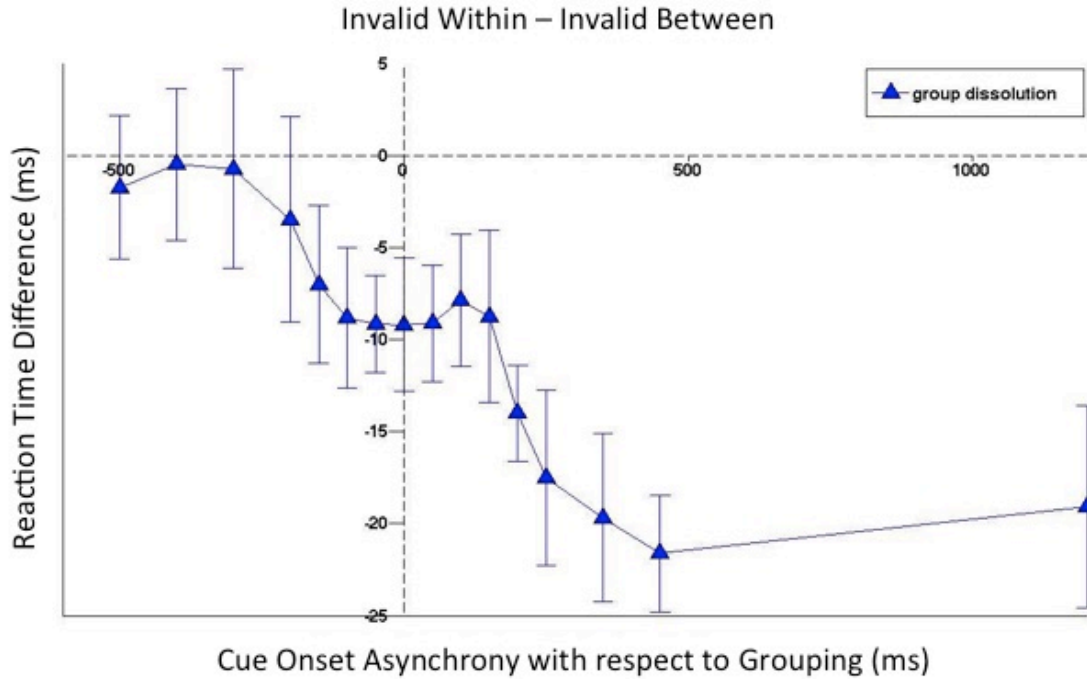


Fig 3.7. Mean Reaction-Time Difference ($\pm$ standard errors) for Invalid Within – Invalid Between in Experiment 2 (dissolution of groups) as a function of COA_G . The negative difference indicates attentional facilitation of grouping.

However, as discussed in the introduction, the concept of “object” remains ill defined. One possible perspective is to consider “objects” as outcomes of the perceptual grouping process, a view that provides a natural connection between the two processes of complexity reduction, viz., attention and perceptual grouping. In fact, in a previous study, it has been shown that attentional resources are allocated to entire groups, highlighting the synergy between these two processes (Gonen et al. 2014). Gonen et al. (2014) examined the case in which perceptual groups were already established and hence were in steady state. In a natural environment, perceptual groups spontaneously form and dissolve, as it is in the case of an animal in camouflage starting to move or stopping on a camouflaging background. When the animal moves, the grouping of its parts based on

common motion reveals the animal as a whole. When the animal stops, the common motion information vanishes and the animal vanishes in camouflage. In this study, our goal was to bring the investigation into a more ecological setting by addressing how exogenous attention is allocated during the formation and the dissolution of perceptual groups.

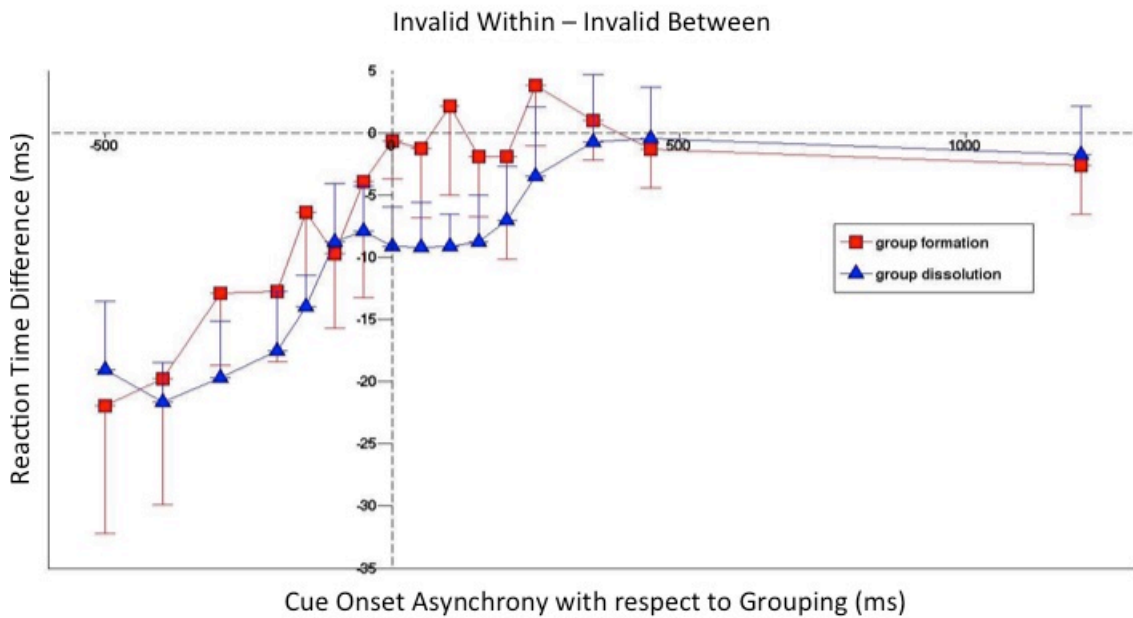


Fig 3.8. Data from Figs 4 and 7 are plotted together to compare the time-course of attentional facilitation by grouping during the formation and the dissolution of groups. The dissolution data are flipped around the y-axis to take into account the fact that COA_G represents asynchrony with respect to the beginning and the end of the groups in Experiments 3.1 and 3.2, respectively. To reduce clutter, group formation and dissolution data are presented only with $-SEM$ and $+SEM$, respectively.

We observed attentional benefits of perceptual grouping during both the formation and the dissolution of groups. Fig 3.8 shows the mean RT difference for both experiments. Because COA_G is with respect to the beginning and the end of the group in Experiments 3.1 and 3.2, respectively, we flipped the results of Experiment 3.2 with

respect to the y-axis in order to compare directly with the results of Experiment 3.1. Since we do not know the relative latency between the time the cue is processed in the brain and the dynamics of grouping processes (Purushothaman et al. 1998; Ogmen et al. 2004), we cannot reach conclusions about the brain timing of attention and grouping. We can, nevertheless, compare directly group formation and dissolution data since they used identical stimulus parameters. As seen in Fig. 3.8, the time-course of attentional benefits of grouping is remarkably similar in the case of group formation and dissolution, operating within a half-second time frame. We can also observe an important difference for the COA_G values between 0 and +500 ms. Whereas, during group formation RT difference reaches zero at $COA_G = 0$ and after, a persisting effect is observed during group dissolution within this interval. This effect is akin to other persistence effects, such as visible persistence. In terms of raw RTs (Figs. 3.3 and 3.6), we observed an increase in RTs when grouping is present compared when it is not. Hence, overall, grouped stimuli tend to slow down absolute reaction times while giving an attentional advantage to all elements of the group.

Taken together, our results reveal the dynamics of how attention and grouping work in synergy during the transient period when groups form or dissolve.

Chapter 4. Interactions between Endogenous and Exogenous

Attention using Static and Dynamic Groups

4.1. Introduction

When we operate in a natural environment, our behavior consists of both volitional and reactive acts. For example, while walking in a city street, we may be under volitional control looking for a specific store and at the same time we may be reacting to the motion of objects around us so as to avoid collision with cars or other pedestrians. Attentional processes control how we allocate our processing resources and attentional orienting is divided into two main categories, endogenous attention and exogenous attention, that are specialized for volitional and reactive control, respectively (Posner, 1980; Jonides, 1981; Weichselgartner & Sperling, 1987; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Cheal & Lyon, 1991; Egeth & Yantis, 1997; Carrasco 2011; Boi et al., 2011). Endogenous (top-down) attention is slow, allocated by volitional control to a stimulus (e.g. an object) or location. Exogenous (bottom-up) attention is the fast, involuntary, reflexive component of the visual attention. It is relatively faster compared to endogenous attention. The general consensus between the two orienting mechanisms is that they are in a continuous rivalry with each other (Godijn & Theeuwes, 2002; Yantis, 1998, 2000, 1990).

A commonly used paradigm to examine endogenous and exogenous attention is Posner's double cueing paradigm (Posner, 1980; Posner & Cohen, 1984, Moore et al., 1988), in which a target is preceded by a peripheral or a central cue. Endogenous attention is typically summoned by a central cue, such as an arrow placed at the center of

the screen (within the focus of attention of the observer) and pointing to the potential location of the target. The observer is given a task that s/he is executing under volition according to the interpretation of the information carried out by the central cue (e.g., which direction is the arrow is pointing to?). Based on this interpretive process, endogenous attention allocates resources to improve the behavioral outcome. A peripheral cue is very brief abrupt, and is generally presented outside of the focus of attention. It generates a reactive process whereby exogenous attention allocates resources to the location of the peripheral cue. Generally stimuli presented at the cued locations require less time to detect and identify compared with the uncued locations, leading to a conclusion that attentional resources are allocated to the cued location. Exogenous and endogenous attention differ both qualitatively and quantitatively. Exogenous attention's effect is more seen at early stages of processing. It affects the stimulus enhancement, external noise reduction, and perceptual processing in object-based coordinates. On the other hand, endogenous type of orienting works at late stages of processing (Chica et al., 2007; Chen et al., 2012; Chica et al., 2013). Memory load can disrupt endogenous attention performance, whereas exogenous attention is independent from the memory load (Chica et al., 2006; Chica et al., 2013). Müller and Rabbit (1989) discovered that peripheral and central cues result differently over target detection. The spatial orientation is much faster when it is cued with a peripheral (exogenous) cue compared to a central (endogenous) cue. Another difference between the two-orientation mechanisms is that the deployment of exogenous attention is not affected by additional memory tasks (Jonides 1981). Jonides demonstrated that while exogenous allocation is spread on objects, endogenous allocation doesn't have to spread on the cued object. Depending on the

stimulus-onset-asynchrony (SOA), exogenous attention can create inhibition of return instead of a facilitatory effect over target detection/discrimination (Klein, 2004, 2009; Klein and Shore, 2000; Posner, 1984).

Although a large body of evidence supports the fact that endogenous and exogenous attention are two distinct processes tuned to the different demands of volitional and reactive resource-allocation problems, in a natural setting, they are likely to operate often concurrently. For example, while focusing on a reading task via endogenous attention, a movement or noise in the room can simultaneously engage exogenous attention. Hence, it is important to determine how these two processes operate concurrently: Do they exhibit independent additive/subtractive effects or do they interact? Even though the two processes are considered to be distinct, several studies concluded that they interact (Busse et al., 2008; Chica et al., 2008; Chica et al., 2013; Posner et al., 1985; Jonides et al., 1981; Chen et al., 2012; Grubb et al., 2015). Neurophysiological studies suggested that endogenous and exogenous attention have distinct but overlapping neural substrates (Busse et al., 2008, Khayat et al., 2006). These studies hypothesize the role of the dorsal fronto parietal region as the region for a common processing center for both type of orienting, and the ventral fronto parietal region for task relevant incidents (Corbetta et al., 2008). It is possible that the overlap in neural substrates can induce strong interactions between these two processes.

Findings reported in the literature are mixed (review: Chica et al., 2013) and part of the problem arises from the fact that the deployment of attention depends on several factors, including the predictive value and the timing of the cues, as well as the task. For example, Müller and Rabbitt (1989) reported that the effect of an exogenous cue was

contingent on the validity of the endogenous cue. For a valid central cue, a compatible (i.e., valid) peripheral cue enhanced performance whereas an incompatible (invalid) peripheral cue reduced performance. For an invalid central cue, the peripheral cue enhanced performance when it was valid but reduced performance when it was invalid. It may be argued that a central cue that is not 100% valid may cause the observer to adopt a strategy in which some of attentional resources are allocated to the non-cued parts of the stimulus and hence allowing capture of other cues, such as peripheral cues. In fact, Yantis & Jonides (1990) showed that as the validity of the central cue increased, its effect became more resistant to modulations by peripheral cues and it was immune to modulation when the central cue was 100% valid.

Previous studies reported different outcomes for detection and discrimination tasks (Chica et al., 2013). Our main aim was to examine whether endogenous and exogenous attention operate independently or interact using the same paradigm with minimum changes for both type of tasks (discrimination and detection). Another important aspect of ecological environment is that it contains both static and moving objects. The bulk of research used static stimuli and very few studies examined whether and how the findings from static stimuli would extend to dynamic stimuli (Gonen et al., 2014; Gonen & Ogmen 2016). Hence, a second aim of our study was to use a single type of paradigm for both static and dynamic stimuli in investigating potential interactions between the two attentional processes.

4.2. Experiment 4.1

The goal of the experiment was to investigate the possible interactions between endogenous and exogenous attention while using both static and moving objects. We used Posner's double-cuing paradigm (Posner, 1980). Our stimuli consisted of squares that formed two groups based on color similarity (red and blue; Fig 4.1). In order to investigate static vs. moving stimuli, the squares were either static on the screen or rotated around the center of the screen. The task was either detection or discrimination. The validities of the exogenous and endogenous orienting cues were systematically controlled. Hence, our experiment was designed to investigate the interactions between exogenous and endogenous orienting mechanisms by taking into account task dependency, cue validity, and stimulus mobility. Details of experimental design are given below.

4.2.1. Methods

4.2.1.1. Protocol and Subjects

The experiment reported in this study was conducted in accordance with the federal regulations, 45 CFR 46, the ethical principles established by the Belmont Report, and the principles expressed in the Declaration of Helsinki, according to a protocol approved by the University of Houston Committee for the Protection of Human Subjects. Twelve University of Houston students participated in the experiment. All subjects had either normal or corrected-to-normal vision. Except the first author being one of the subjects, all other subjects were naïve to the purpose of the experiments. Each subject's

participation was voluntary and each gave his/hers written informed consent according to a protocol approved by the University of Houston Committee for the Protection of Human Subjects.

4.2.1.2. Apparatus

We presented the stimuli on a 20-inch NANA FlexScan color monitor in a dark room. The resolution of the display was set to 656 X 492 pixels with 100 Hz frame rate. We used a video card (Visual Stimulus Generator; VSG 2/3) manufactured by Cambridge Research Systems for stimulus generation. A head-and-chin-rest was fixed at a distance of 1 meter from the display monitor mentioned above. The screen size was 23° X 17.5° and one pixel corresponded approximately to 1.7 arcmin. We used joystick interfaced to the VSG board to measure reaction times.

4.2.1.3. Stimulus and Procedure

Fig. 4.1 shows the stimulus configuration for the experiment. The stimuli consisted of 6 squares, each square with 1.6° X 1.6° visual angle dimensions and a luminance of 4 cd/m^2 . The stimuli were either stationary or rotating around a fixation point, which was a white plus sign (+) placed in the center of the monitor. Half of the squares were blue (CIE coordinates: 0.3044, 0.6541, 4), the other half was red (CIE coordinates: 0.3776, 0.3808, 4) making a randomly chosen two different Gestalt groups on a black background (0 cd/m^2). The center of the squares were placed on an invisible circle with a diameter of 3° visual angle with an angle difference of 60° in order to keep

the eccentricity constant. For the dynamic case scenario, the direction of rotation, clockwise or counter-clockwise, was randomized from trial to trial. There were two different cues: endogenous cue which was a thin gray line indicating a single square and an exogenous cue which was one of the squares changing its orientation abruptly and returning to its initial orientation. Each trial started with a preview: six squares with a randomly chosen six starting positions (along the invisible circle with 60 degrees separation). If it's a dynamic trial, the squares started their motion with the onset of the preview. After the preview period of 500 ms, the endogenous cue was shown for 500 ms. In the static case, the cue was stationary, in the dynamic case, the endogenous cue also kept turning along its invisible circle. ISI 1 was either 300 or 500 ms right after the endogenous cue. After ISI 1, exogenous cue was introduced for 100 ms. The exogenous cue altered the orientation of one square and returned back to its original orientation. The complete exogenous cue duration was 100 ms. After the exogenous cue; there was another ISI (ISI 2, Fig 10). ISI 2 was followed after the offset of the exogenous cue and the target was presented for a maximum period of 1000 ms (see Fig 4.2-4.3-4.4). The task was to either detect the target which was an X inside a square, or to discriminate (whether the target arrow looked to left or right) it and press the joystick button as soon as possible. Including the catch trials, the stimuli had 10 target options with different percentages (see table 4.1).

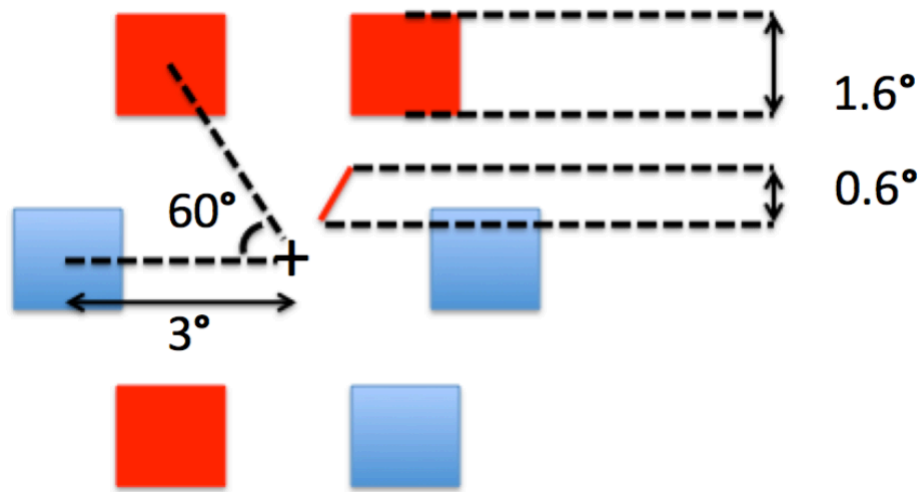


Fig 4.1. Stimulus configuration for Experiment 4.1

Table 4.1. All target options are listed below with their percentage occurrences.

	Endogenous Validity	Exogenous Validity	Percentage
1	Valid	Valid	6%
2	Valid	Invalid Within	27%
3	Valid	Invalid Between	27%
4	Invalid Within	Valid	5%
5	Invalid Within	Invalid Within	5%
6	Invalid Within	Invalid Between	5%
7	Invalid Between	Valid	5%
8	Invalid Between	Invalid Within	5%
9	Invalid Between	Invalid Between	5%
10	Catch	Catch	10%

In order to keep the percentage balance between different groups, the invalid within percentages and the invalid between percentages had to be equal among the same categories. For example in endogenously valid trials, exogenously invalid within trials had to have the same percentage as exogenously invalid between trials. Second and 3rd

target options, 5th and 6th, 8th and 9th had to be equal. Also on the contrary 4th + 5th + 6th had to be equal to 7th + 8th + 9th. In order to have an effective endogenous cue, the validity had to be kept above chance and possibly with a high percentage. However exogenous validity had to be kept at chance level (We had 6 squares, the chance level was 16.6%). We set the levels 60 % and 16 % respectively. “Invalid Within” signified that the cued element and the target had the same color, whereas “Invalid Between” signified that the cued element and the target had different colors. All the target options were presented in randomly ordered trials. As said earlier, the endogenous cue was predictive at 60 % of the trials.

However the exogenous cue was not predictive of the target location (16% validity). In order to protect the balance between within object trials and between object trials, invalid within and invalid between percentages were kept equal for each type of cue. Each session had 48 trials for each target option, and each subject had to complete 4 sessions. As a total, for each condition (static vs. dynamic, and detection vs. discrimination), 10 target options (including catch trials) x 48 x 4 made 3840 trials. 7680 trials were recorded from each subject. Before recording the data for every subject, 60 trials for each target option were performed for training purposes.

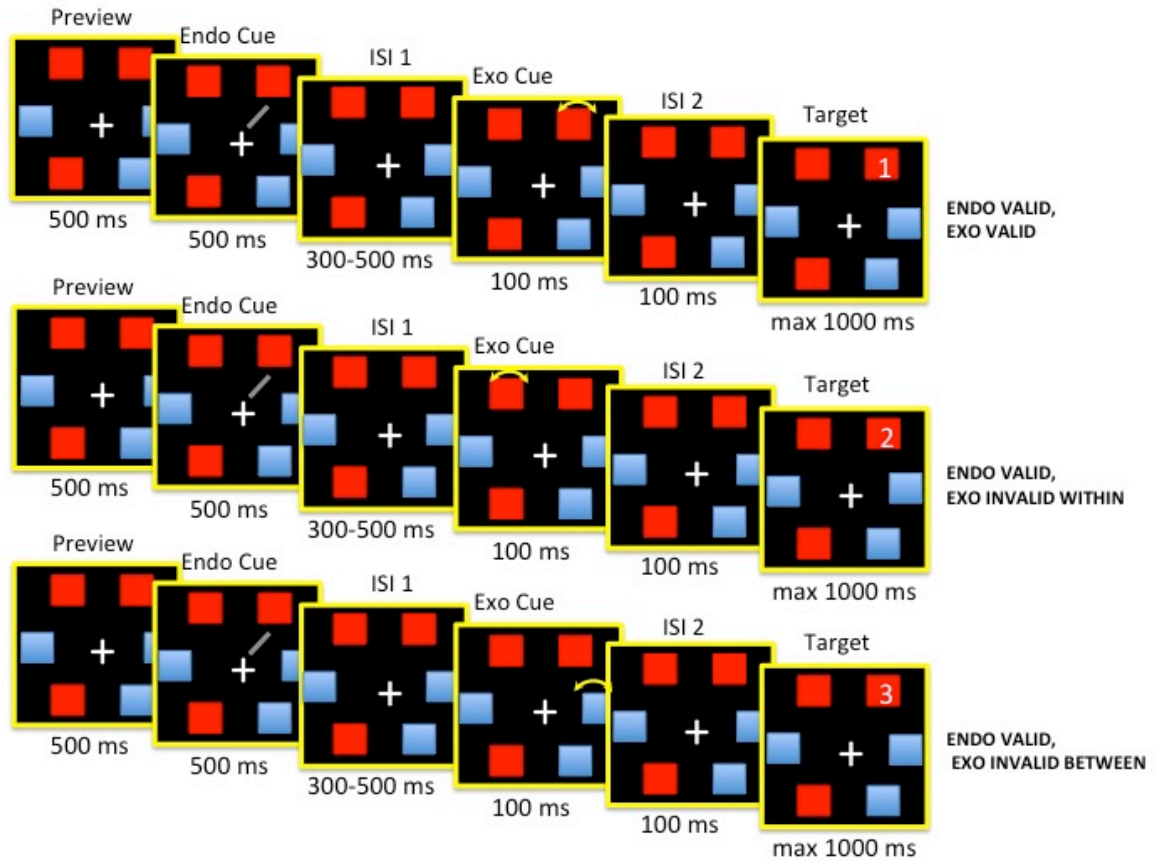


Fig 4.2. First Schematic Representation of the Exp 's stimuli (static case). When the endogenous cue is valid, exogenous cue can either be valid, invalid within (same color as the target but different one), or invalid between (other color with respect to the one, which cue is indicating). The trials start with a preview period of 500 ms. The preview is followed by the endogenous cue, which a central line showing one out of six squares. After the offset of the endogenous cue, ISI 1 comes (its duration is either 300 ms or 500 ms). ISI 1 is followed by the exogenous cue for 100 ms. The exogenous cue is an orientation change of one square. After ISI 2 of 100 ms, the subjects are required to make either detection or discrimination task while they see the target. For detection, the target is an X letter inside a square. For discrimination, the target is an arrow pointing to either right or left. The target stays on the screen for a maximum duration of 1000 ms.

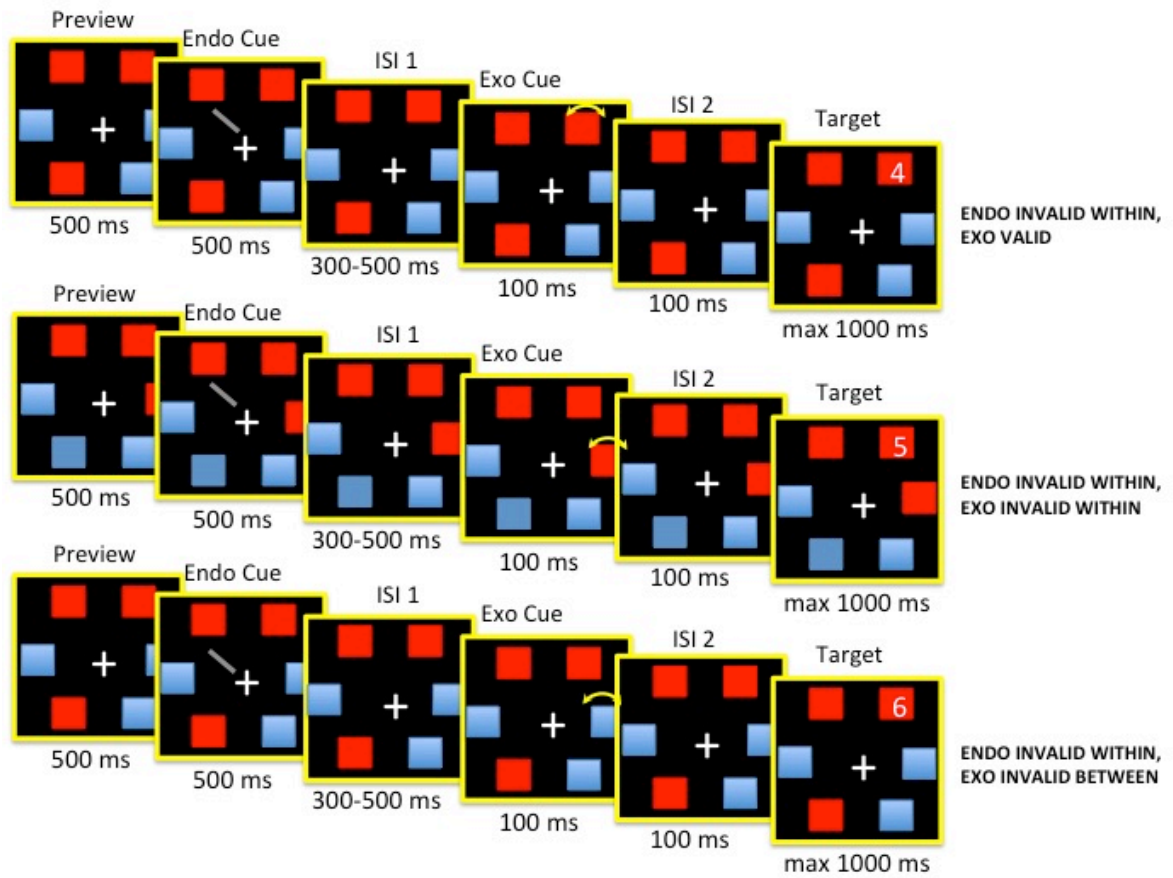


Fig 4.3. *Second Schematic Representation of the Exp 's stimuli (static case). When the endogenous cue is invalid within (the endogenous cue points to a red square, the target will be inside another red square), exogenous cue can either be valid, invalid within, or invalid between.*

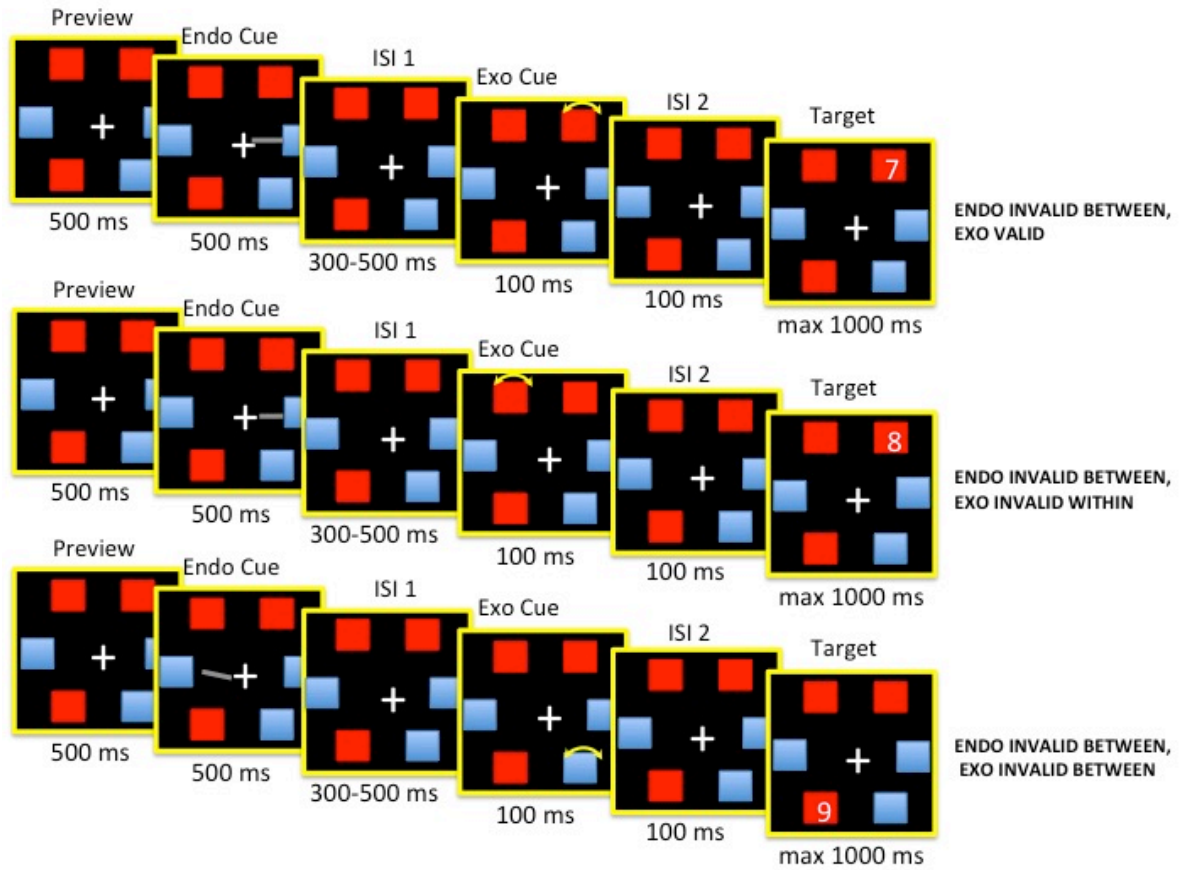


Fig 4.4 Third Schematic Representation of the Exp 's stimuli (static case). Endogenous Cue is invalid between (endogenous cue is pointing the "other color" and not correct in terms of location).

4.2.1.4. Results and Discussion

Mean reaction times and standard errors were compared. Reaction times less than 150 ms and greater than 1000 ms were excluded from all analysis corresponding to 1.3 % of the whole. Reaction time data were analyzed by three-factor (validity, task, mobility) repeated measures ANOVA revealing main effects for all three factors. ($F(8,88)=61.716$, $p<0.001$, $\eta_p^2 = 0.411$ for validity, $F(1,11)=22.286$, $p<0.003$, $\eta_p^2 = 0.593$ for mobility, $F(1,11)=72.692$, $p<0.001$, $\eta_p^2 = 0.831$ for task) Accuracy in catch trials was higher than

98.1%. Fig 4.5 shows the whole data for all 9-target types. In all four conditions, the fastest target option was the valid/valid condition and the slowest was the invalid between / invalid between condition. The detection conditions were faster compared to discrimination.

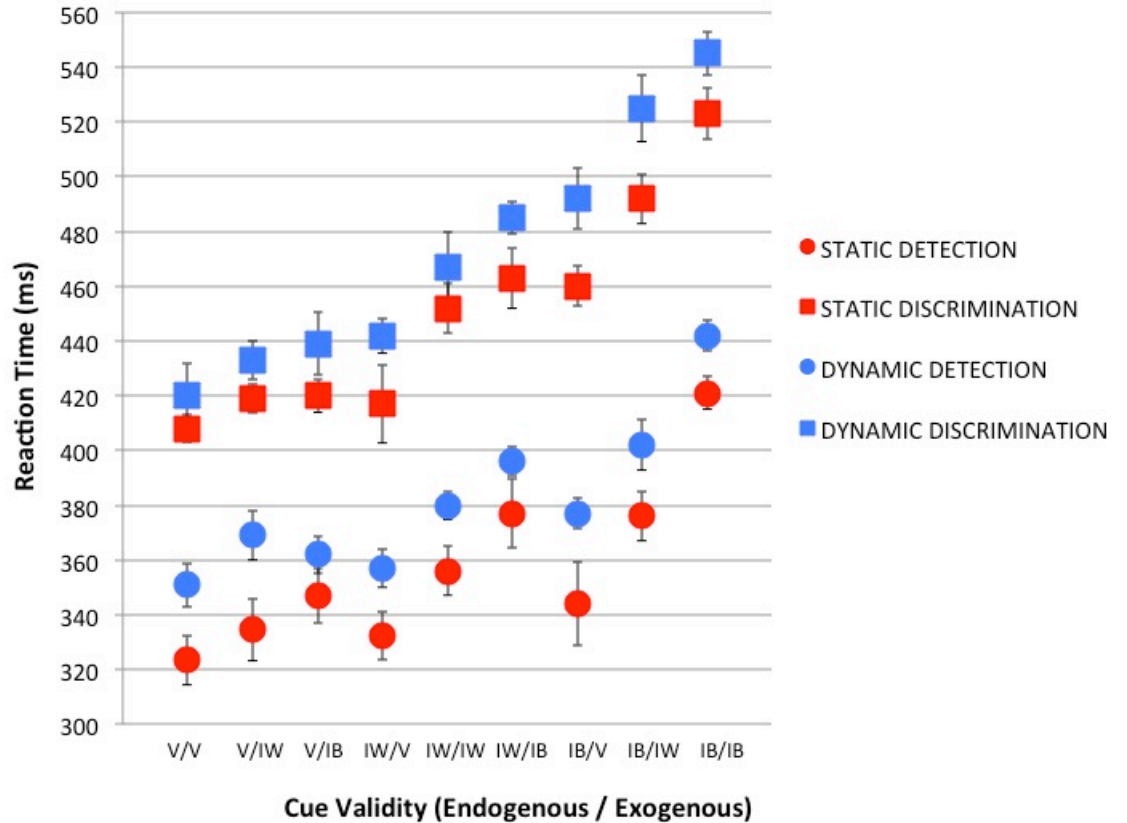


Fig 4.5. Mean Reaction Times ($\pm$ standard errors) as a function of endogenous and exogenous cue validity. Detection conditions are significantly faster than discrimination conditions. In all conditions, valid/valid is the fastest compared to the rest.

There was no interaction between mobility and task ($F(1,11)=0.371$, $p=0.497$, $\eta_p^2=0.241$), again, no interaction between mobility and validity ($F(8,88)=0.463$, $p=0.744$, $\eta_p^2=0.061$), but we observed a significant interaction between task and validity ($F(8,88)=4.568$, $p=0.011$, $\eta_p^2=0.142$). Three-way interaction was not significant

($F(8,88)=0.549$, $p=0.814$, $\eta_p^2=0.117$). Inspection of the data, and the lack of interactions between mobility and the other factors indicated that similar mechanism operate for static and moving stimuli; however reaction times tend to be slower in the case of moving stimuli; We replotted in Fig 4.6 the data in Fig 4.5 organized according to task and stimulus-type (mobility) leading to 4 conditions {task (detection, discrimination), mobility (static, dynamic)}. In each of these conditions, we ran a 2 factor (validity; cue-type) ANOVA repeated measures (static detection, static discrimination, dynamic detection, and dynamic discrimination). In both discrimination conditions, we have found interaction between validity and cue-type (for static discrimination $F(1,11)=11.251$, $p=0.038$, $\eta_p^2=0.597$, and for dynamic discrimination $F(1,11)=7.115$, $p=0.013$, $\eta_p^2=0.451$).

On the other hand in detection conditions, this significant interaction was absent (for static detection $F(1,11)=3.103$, $p=0.141$, $\eta_p^2=0.301$, and for dynamic detection $F(1,11)=12.913$, $p=0.061$, $\eta_p^2=0.612$). However, inspection of the left panels in Fig. 4.6 show that there is a non-significant but similar tendency in the detection task compared to discrimination task: The effect of exogenous validity becomes weaker when the endogenous cue is valid, as observed in the discrimination task; this interaction tendency, however, does not reach significance. Previous research showed that the facilitatory effects of exogenous cues are larger for discrimination tasks compared to detection tasks (Lupiáñez et al., 2001). Hence the failure to observe interactions in the detection tasks may be due to the smaller effect size observed for this task. To clarify on the possible interaction of the detection tasks, we conducted a Bayesian Anova, which is independent of effect size. The Bayesian Repeated Measures Anova revealed a Bayesian Factor of

1.56 (full interaction model: [Cue type + Validity + {Cue type * Validity}] vs. main effect model: [Cue type + Validity]) for the interaction involving both factors (validity and cue type). The result can be taken as anecdotal (weak) evidence for the interactions.

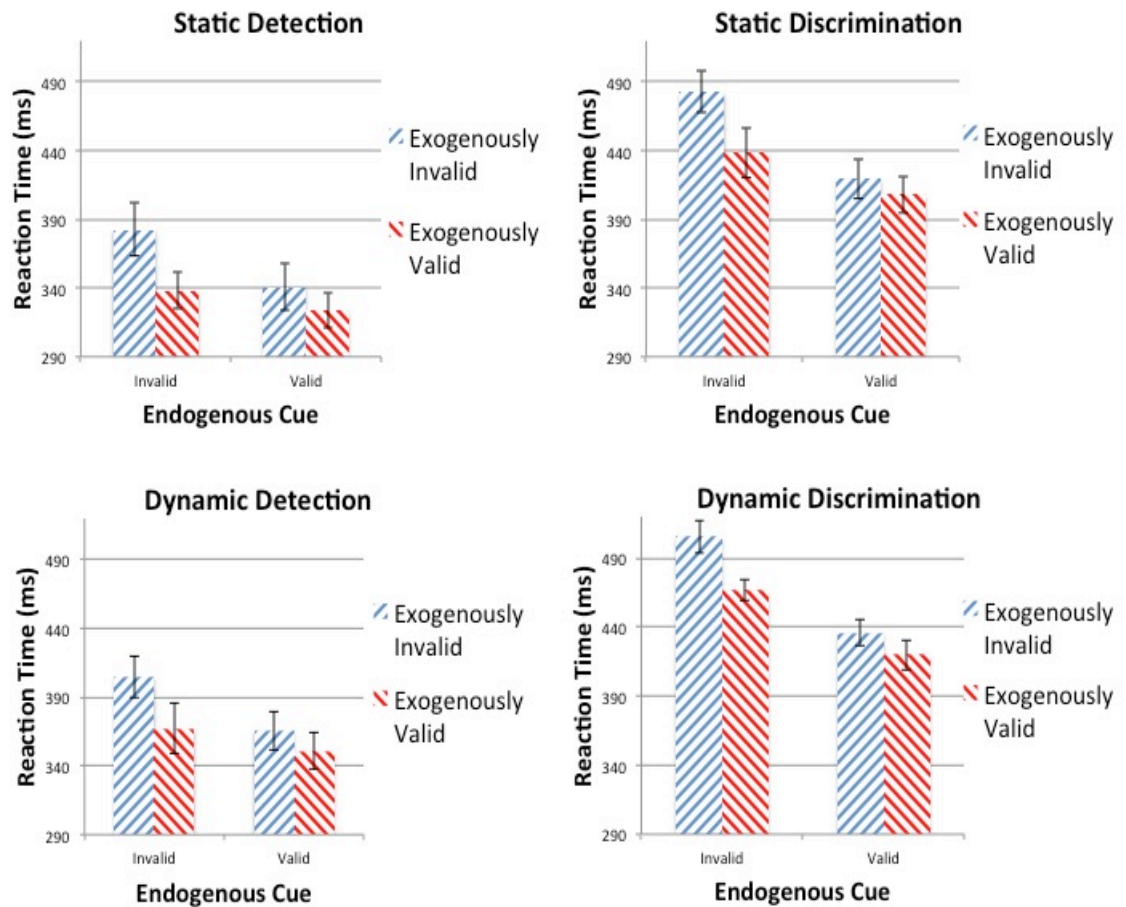


Fig 4.6. Mean Reaction Times ($\pm$ standard errors) as a function of endogenous and exogenous cue validity for different trial types.

To further analyze the differences in the discrimination conditions, we divided each of the 2 discrimination conditions into 2 and conducted 4 paired sample t-tests to understand the effects of attentional orientation on each other. The Bonferroni corrected

confidence interval (α) was adjusted from 0.05 to 0.0125. Paired sample t-tests results showed that when the endogenous cue was invalid, there was a significant difference between a valid exogenous cue and invalid exogenous cue (see Table 4.2). However when the endogenous cue became valid, the exogenous cue's effect was lost.

Table 4.2. Paired sample t-test results showing significant test results when the endogenous cue is invalid for both static and dynamic stimuli.

Condition	Endo Val./ Exo Val.	Endo Val./Exo Val.	Results
Static Disc.	Invalid / Invalid	Invalid / Valid	t(11)=4.913, p=0.001, d=1.78
Static Disc.	Valid / Invalid	Valid / Valid	t(11)=0.551, p=0.512, d=0.11
Dynamic Disc.	Invalid / Invalid	Invalid / Valid	t(11)=5.428, p=0.001, d=1.25
Dynamic Disc.	Valid / Invalid	Valid / Valid	t(11)=0.844, p=0.217, d=0.29

4.3. General Discussion

The main aim of this experiment was to investigate interactions between the endogenous and exogenous attention. We used peripheral cues for exogenous attention and central cues for endogenous attention. Previous research showed that task demands and cue validity could affect the operation of exogenous and endogenous attention. Moreover, the ecological environment contains not only static but also moving objects. Very little is known on how attentional processes are allocated to moving stimuli. Hence, our goal was to examine systematically interactions between the endogenous and exogenous attention with an experimental design that takes into account task demands, cue validity, and stimulus mobility.

In terms of task demands, as expected, the detection task required significantly less time compared to discrimination task. We found significant interactions between endogenous and exogenous orienting systems when the task was discrimination. The interaction did not reach significance when the task was detection, but a tendency similar to that found in the discrimination task is observed though Bayesian statistics returned only weak evidence for the interactions.

The interaction between the two orientating types depends on the validity of the cues. When the endogenous cue was valid, the strength of the exogenous cue was weakened. The endogenous cue was significantly more dominant than the exogenous cue. Also we found main effect of mobility indicating that static and dynamic stimuli reaction times were significantly different.

Four different models have been proposed regarding the relationship between exogenous and endogenous attention (Berger & Rafal, 2005): The first and the oldest view posits that there is only one mechanism and both orienting types can access it (Posner, 1980; Jonides, 1981). The second one sees the matter as two different modes sharing the same resource pool. The effect of endogenous attention on exogenous attention is possible but the inverse is seen as impossible (Warner et al., 1990; Yantis & Jonides, 1990; Theeuwes, 1991). The third one is the complete opposite of the second model: whereas the effect of exogenous attention on endogenous attention is possible but the inverse is not possible (Müller & Rabbit, 1989). The last model sees the system as two completely separate mechanisms where both exogenous and endogenous attention can have interactions on each other (Müller & Humphreys, 1991). Part of the problem in

distinguishing between these models is that the outcome depends strongly on the task, validity of the cues, and even temporal parameters (Lupiáñez et al., 2001).

As it is the case with the behavioral studies and models, neuroimaging studies are not in line with each other either. The temporal resolution of the fMRI technique makes it hard to capture the brief abrupt effects of the exogenous orienting. Research studying brain-damaged patients showed that patients having left visuospatial neglect, also lack the ability to process consciously stimuli presented on the contralateral side, affecting exogenous orienting but preserving the endogenous orienting abilities (Bartolomeo & Chokron 2002). On the other hand, Hopfinger and West (2006) recorded event-related potentials (ERPs) and reported, “*two partially separate but interacting attention systems*”. Several studies reported that these two types of orienting depend mostly on common brain regions (Corbetta et al., 1993; Kim et al., 1999; Nobre et al., 1997; Rosen et al., 1999; Peelen et al., 2004).

We conclude that interactions between endogenous and exogenous orienting mechanisms are similar for static and dynamic stimuli and these interactions depend on task demands and the reliability of cues. From an ecological point of view, since these orienting mechanisms are often deployed concurrently, it makes sense that they interact and that their interactions depend strongly on the context.

Chapter 5. Small Sample Advantage during Self-Guided Exploration

5.1. Introduction

The stimulus contingency detection in the environment is one of the crucial functions of the human brain. The detection property that we possess facilitates active exploratory behaviors; making contingency detection is an essential part of human intelligence and behavior. How to sample the environment, make decisions using the sampled environment are foundational issues in perception and cognition. Several models explain human perception and decision-making as means to optimize a given criterion. Yet, several studies studying perception, cognition, and decision-making concluded that human behavior differs greatly from decision-making models. The reason for this “sub-optimal” behavior is still unknown. For example, according to statistical theory, humans are expected to maximize their sampling in order to make a decision. However, frequently humans choose small samples over large samples (Fiedler and Kareev 2006; Goldstein and Gigerenzer 2002, Hertwig and Todd 2003, Newport 1990) and present higher confidence in their decisions (Vickers et al., 1985). A general understanding of perceptual and cognitive processes is not possible until we understand why we prefer small samples compared to large ones. It might be “quick gut decisions”, fatigue, opportunity costs, and limited short-term memory (Kareev, 2000). Rakow et al. (2008) discovered that there is a relation between the sample size used to make a decision and working memory capacity. Studies favoring small samples over large samples (Goldstein and Gigerenzer 2002, Hertwig and Todd 2003, Newport 1990) remained questionable

since they did not possess a firm background (Evans and Buehner 2011, Fiedler and Kareev 2006, Kareev and Fiedler 2006, Kareev and Fiedler 2011).

More recently a statistical decision framework has been proposed in which small samples surpass large samples (Small Sample Advantage, SSA) in decision-making in detecting stimulus contingencies (Fiedler and Kareev, 2006). In other words, according to Fiedler and Kareev's approach, humans do not seek to maximize the number of samples but instead purposefully keep it small.

Our goal was to understand how perceptual and cognitive processes operate in real time in a natural dynamic scene. From an evolutionary perspective, humans are active explorers, and it is crucial to understand how they collect their information from the environment, and how it is used to make decisions and guide learning processes. In two experiments, we tested the small sample advantage theory under self-guided exploration.

5.2. Approach

In our study, we investigated the hypothesis that small samples lead to better decisions than large samples for detecting stimulus contingencies during self-guided exploration. We used Fiedler and Kareev's (2006) SSA theory in which they proposed a satisficing-choice model for contingency detection where small samples are advantageous compared to large samples. In contingency calculations, a problem is considered in which the subject needs to make a contingency-based decision between two

options according to his/her observations of the stimulus. Usually, this problem is represented by a 2x2 contingency table. The contingency can be computed by

$$\Delta = a/(a+b) - c/(c+d). \quad (\text{Eq. 5.1})$$

Table 5.1. 2X2 Contingency table

	Feature 1	Feature 2
Option 1	a	b
Option 2	c	d

Each cell (a, b, c, and d) contains the frequencies of option-feature combinations. There are three different levels to measure the contingency. If one needs to measure the true state of the nature (Δ_e), a, b, c, and d must be taken as the natural frequencies found in the environment. Secondly, if the environment needs to be sampled, a, b, c, and d inside the sample pool must be used to compute the contingency (Δ_s). The final one is Δ_c , which is the cognitive contingency based on the representations of the samples in the brain.

In their stimuli, Fiedler & Kareev used smileys and frownies, representing positive and negative ratings, respectively. To briefly describe their paradigm, the stimuli were divided into two spatial halves. The left and the right halves represented options 1 and 2. The subjects were asked to assess which half (option) contained more smileys. After each trial, subjects were asked to choose “Option 1”, “Option 2” or “No Choice” along with their level of confidence for their decision. As being said, not every trial results with a choice even though samples are being observed. The choice is produced only if the sample has enough superiority of one option over the other. Thus, in order for

a trial to produce a decision, Δ_s needs to be larger than the threshold (t). If it's the other way around, then no choice is produced, the subject declines to make a choice and picks “No choice” option. By a threshold-based model, Fiedler & Kareev (2006) defined the hit and false alarm scenarios. According to the model, a correct choice happens when $\Delta_s > +t$, and an incorrect choice happens when $\Delta_s < -t$. The sample with $-t \leq \Delta_s \leq +t$ produce a “no choice”.

Fig 5.1, taken from Fiedler and Kareev (2006), provides the necessary understanding. It shows the more broad distribution of the small samples compared to the large samples, producing more samples above the threshold (t).

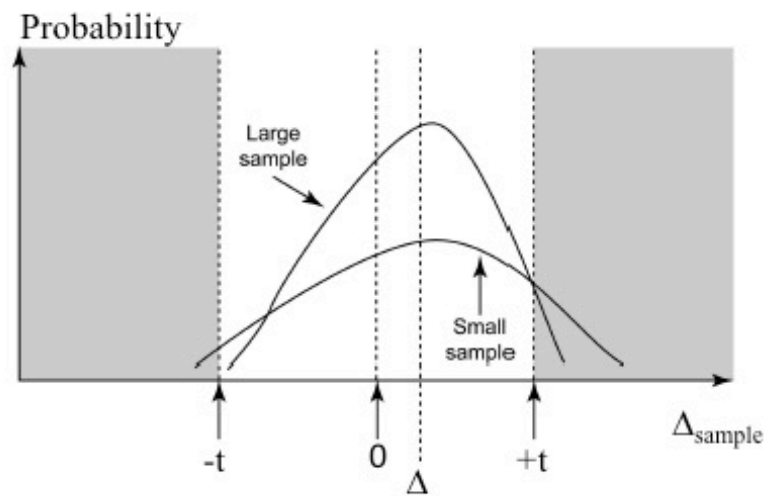


Fig 5.1. Sampling distributions comparing large and small samples for a positive Δ_s . Reproduced from Fiedler and Kareev (2006).

One of the problems with their design was that subjects were not allowed to choose their sample-size but instead they were forced on either to 16 or 32 samples (Exp 2). This approach led the subjects to actively reject information, which is not same as not

having information (Vickers et al., 1985). Their results showed less than 10% “no choice” indicating that subjects used a low t value. SSA does not hold for low t values. Fiedler & Kareev (2006) showed that SSA is present only when the observed contingency (Δ_s) is larger than a given threshold t .

5.3. Experiment 5.1 & 5.2: Homogeneous and Heterogeneous Displays

Our study consisted of two parts: homogeneous displays and heterogeneous displays. The goal of the study was to test the hypothesis that small samples lead to better decisions than large samples for detecting stimulus contingencies during self-guided exploration.

5.3.1.1. Protocol and Subjects

All experiments were conducted according to a protocol approved by the University of Houston Committee for the Protection of Human Subjects, in accordance with the federal regulations, 45 CFR 46, the ethical principles established by the Belmont Report, and the principles expressed in the Declaration of Helsinki. Fifteen University of Houston students participated in each experiment. All subjects had either normal or corrected-to-normal vision. With the exception of the first author who served as subject, all subjects were naïve to the purpose of the experiments. Subjects’ participation was voluntary and they gave their written informed consent according to a protocol approved by the University of Houston Committee for the Protection of Human Subjects.

5.3.1.2. Apparatus

Stimuli were presented on a 22-inch Sony color monitor, with a white background. The resolution of the display was set to 800 X 600 pixels with a 100 Hz frame rate. Generation of the stimuli was made possible by a video card (Visual Stimulus Generator; VSG 2/5) manufactured by Cambridge Research Systems. The screen size was approximately 25.3 ° X 19.25° and each pixel corresponded to 1.14 arcmin. We controlled and recorded eye movements through SR Research Eye Tracker Eyelink II.

5.3.1.3. Predictions

We tested 7 predictions that are in contrast with large-sample seeking strategies. These predictions are explained below. In both experiments, the subject explored the stimulus by self-guided eye movements. The subjects terminated the trials when they want. We tested Predictions 1-5 for homogeneous displays and Prediction 1-7 for the heterogeneous display part.

We assumed the sampling stage and for definiteness, let Δ_e be positive. Fig 5.2 shows the Δ_s distributions for both small and large samples. Statistical theory suggests that the two distributions will be both centered on Δ_e and small sample will be more widely distributed. When $\Delta_e > 0$, it means that option 1 corresponds to correct choice, and option 2 corresponds to incorrect choice. So hit rates correspond to the area under $\Delta_s > t$, and false alarm rates correspond to the area under $\Delta_s < -t$. “No Choice” corresponds to area under $-t < \Delta_s < t$. As seen from Fig 5.2, small sample distribution increases hits as well as false alarms compared to large sample distribution. Though, since $\Delta_e > 0$, there will

be a bigger increase in hits compared to false alarms. According to this principle, we extract these key predictions of SSA:

Prediction 1: Assume that the observer chooses N samples to make the decision. Then, there will be a *negative correlation* between Δ_s (computed over those N samples) and N . This is because, according to the satisficing choice criterion, N depends on Δ_s : if the first few samples provide large Δ_s that exceeds the decision threshold t , the observer stops, thereby generating large Δ_s values for small N values. In contrast, according to traditional statistical decision making approaches, N should be as large as possible, set according to power considerations and should not depend on the sample received (e.g., one does not stop an experiment if the first few data points support a hypothesis; but collects the entire data according to a preset sample-size).

Prediction 2: As Δ_e gets larger, more of its distribution falls under the $\Delta_s > t$ region, thus the observer is more likely to obtain satisficing evidence in few samples. Accordingly, there should be a negative correlation between N and Δ_e .

Prediction 3: The average Δ_s will be larger than Δ_e . This is because, according to SSA, the observer is seeking small samples to produce clear evidence, which leads to $\Delta_s > \Delta_e$. In contrast, according to the standard statistical approach, the observer should seek large samples so as to obtain $\Delta_s \approx \Delta_e$.

Prediction 4: There will be a *negative correlation* between confidence-ratings reported by the observer and N . This is because, on the average, smaller samples are expected to produce clearer evidence according to the decision criterion used by the

observer. This is the opposite of the prediction of the traditional statistical theory, in which larger samples should lead to higher confidence-levels in decisions.

Prediction 5: Performance (calculated as the difference between correct and incorrect choices) will be *negatively correlated* with N . In contrast, if the observer were to use standard statistical decision rules, larger samples would yield better performance.

Fiedler & Kareev (2006), in their 2nd experiment discovered negative correlation between sample size (N) and performance but their evidence was unclear due to their post-hoc analysis. This result was produced using only the trials that had high decision thresholds. Still, if we take a look in their confidence ratings, there was a small sample advantage compared to large ones (See Prediction 4 above). Their second experiment was a more direct test of SSA because it allowed the subjects to directly control the desired set-size, and then letting the subjects to make decisions. Their results (Exp 2) are in line with Predictions 1, 2, and 3. Confidence ratings as a function of N were not reported (Prediction 4). In order to test Prediction 5, Fiedler & Kareev used two different methods. The first method assigned +1 for each correct, and -1 for each incorrect. The second method weighted these by their assigned confidence level. The first method's results were equivocal, while results obtained by the second method showed small sample advantage.

5.4. Experiment 5.1: Homogeneous Displays

The first experiment had a homogenous distribution of sample size across the stimulus and was designed to analyze additionally the counter-intuitive prediction of

SSA. For example: if the contingency is low, the more items there are in the fixation window, the more, subject is expected to make fixations. More information would cause the subject to sample more. Homogenous displays had three different set size values (3, 5, or 7), and four different contingency values (0.2, 0.4, 0.6, or 0.8). We equally mixed the four different contingency values in each block for every set size, making a total of 3 different blocks.

5.4.1. Procedure

The stimulus consisted of oriented (vertical vs. horizontal) bars (see Fig 5.3 a) with two colors (red or green). The contingency options were the orientation of the bars (vertical, horizontal) and their color {red (CIE XYZ: 0.3776, 0.3808, 4 cd/m²), green (CIE XYZ: 0.0312, 0.5805, 4 cd/m²)}. The background was white (CIE XYZ: 0.3044, 0.6541 with luminance of 2 cd/m²). We set the contingency in the environment Δ_e to 0.2, 0.4, 0.6, and 0.8 and we generated the four entries of the contingency table to match the contingency values. Δ_e values were chosen to span both low and high values so that we can observe both cases when SSA holds and where it does not (see Fig 5.2 A and C). In order to assess spatial attention, eye movements were measured. In contrast with Fiedler & Kareev study, items from the two color categories were equally distributed over the screen (instead of being separated into two halves of the screen). We presented all the items on the screen and the subject was able to sample the stimuli as long as he/she wanted. In terms of sample size, 18 Gaussian windows made 54 items for set-size 3, 90 items for set-size 5, and 126 items for set-size 7. We limited all the stimuli to be inside an invisible circle having a diameter of 5 degrees.

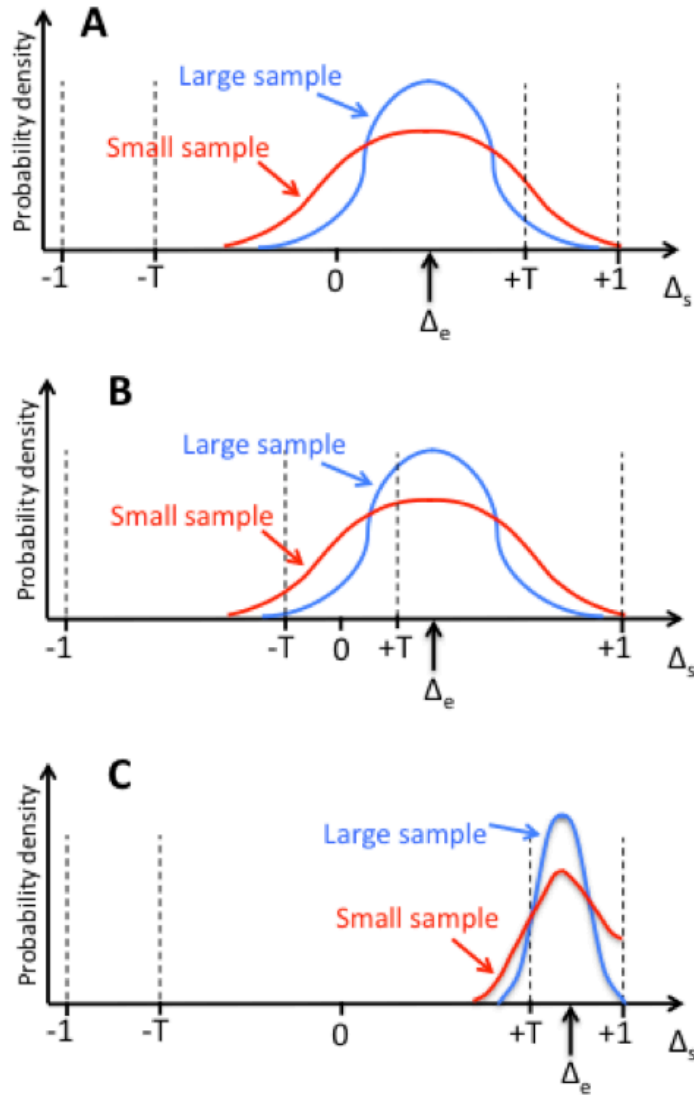


Fig 5.2. Probability density functions for Δ_s for different combinations of Δ_e and t . Assuming Δ_e is positive, Fig 5.1 A shows how the distributions of Δ_s would look like for large and small sizes. Both of them are centered at Δ_e and the small sample distribution is wider compared to large sample distribution. Hit and False Alarms correspond to the areas under $\Delta_s > t$ & $\Delta_s < -t$ respectively. Since $\Delta_e > 0$, and with more dispersion than large samples, small sample based decisions increased more hits than false alarms. In Fig 5.2 B, if $\Delta_s > t$, a decrease in hits is observed for small samples with a possible small increase in false alarms as well. Small sample advantage would only work if the threshold were higher than environment contingency meaning clear-cut evidence. The area under the curve from -1 to $-t$ is larger for small samples leading to more incorrect answers compared to large samples. Fig 5.2 C shows the case scenario, in which a high Δ_e is shown. Choosing a high relatively high t would slightly decrease the small sample advantage over large sample. Similar to Fig 5.2B, the area under the curve from -1 to $-t$ is larger for small samples leading to more incorrect answers compared to large samples. The Small sample advantage does not hold for high Δ_e values. Because Δ_e can't be more than 1, a narrower distribution would result in more advantage.

All the fixation windows were generated inside this invisible circle. Gray Gaussian envelopes hid all the items if they were out of fixation. So subjects were only able to see the information about color/orientation on the fixated Gaussian envelope only.

The subject had to fixate his/her eyes to see the information for each Gaussian envelope. Switching from one Gaussian envelope to another would cause the closing of the former envelope and opening of the latter envelope. The subjects were able to control both the number and the duration of fixations in order to make as natural as possible. By pressing a button in the joystick, the subject was able to terminate each trial. They were asked if the relative frequency of vertical items were higher in (i) red or (ii) green items or (iii) no choice. After answering the question, subjects reported their confidence in their response with a number from 1 to 5. Number 1 being not confident at all, and number 5 being very confident.

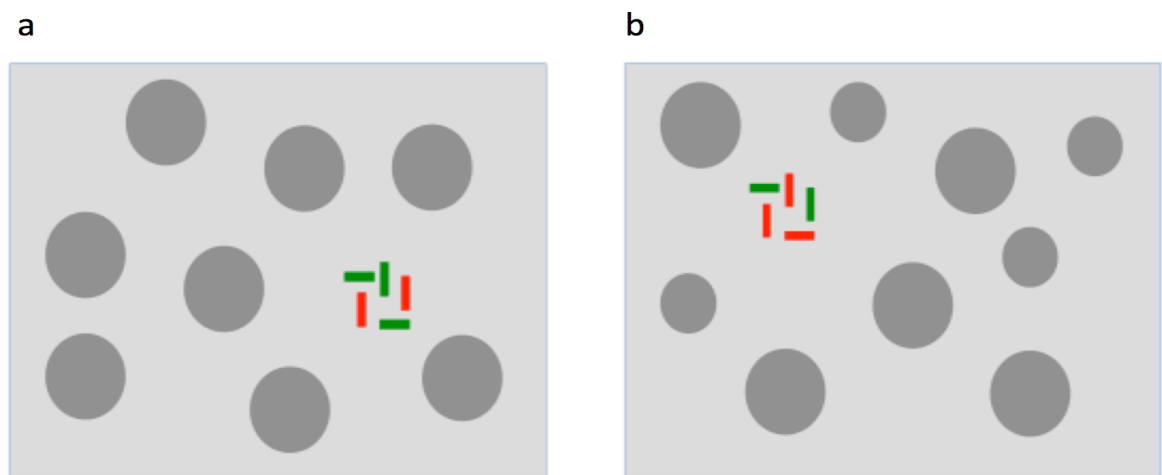


Fig 5.3. Experiment 5.1 & 5.2 stimuli configuration. Gaussian envelopes hide items outside of the fixation region. In part a) Homogenous displays. In the figure set size is equal to 5. In part b) Heterogeneous displays. Because of the heterogeneous display Gaussian envelopes have different diameters.

During training, we gave a feedback after each trial. However, during the experiment, the only feedback the subjects received was at the end of the session. Each correct answer resulted with +1, incorrect answer with -2. There were no penalty for the “no choice” option. The reason to penalize incorrect answers more heavily was to have subjects adopt a high criterion level for choice. All four Δ_e cases were equally mixed in each block. Each set size (3,5 and 7) was blocked. Each subject did 240 trials for each set size, making a total of 720 trials per subject, and 10800 trials for all the subjects.

5.4.2. Results and Discussion

Each trial produced N, Correct/ Incorrect/ No Choice answer, number of fixations, their order and duration, confidence rating and Δ_s . Table 5.2 shows the whole averaged data over 15 subjects. For every set-size, 18 Gaussian windows were created. In terms of sample size, 18 Gaussian windows make 54 items for set-size 3, 90 items for set-size 5, and 126 items for set-size 7.

We analyzed the data with respect to the predictions cited above. In **Prediction 1**, a negative correlation between N and Δ_s was expected. For each subject, we separated the trial-by-trial data with respect to Δ_e values to obtain the N vs. Δ_s values. We calculated 2-tailed Pearson-Correlation tests giving 15 correlations values for each Δ_e values. We then compared the correlation values with 0 by performing one-sample t-tests for each Δ_e values. All correlations between N and Δ_s were significantly negative except when Δ_e was equal to 0.8, indicating a significant small-sample advantage for the remaining contingency values (See Table 5.3). For $\Delta_e = 0.8$, this case was discussed in Fig 5.2 C. If

the environment contingency were close to the positive extremity, a narrower distribution would be more advantageous. In the case of $\Delta_e = 0.8$, $\Delta_s = 0.81$, $\Delta_s \approx \Delta_e$. Δ_s and N was positively correlated for $\Delta_e = 0.8$ case.

Table 5.2. From left to right: correct percentage, correct confidence level, incorrect percentage, incorrect confidence level, no choice percentage, sample size (N), Δ_s , and performance percentage (correct percentage – incorrect percentage) are reported for the homogeneous display.

	Correct	Conf.	Incorrect	Conf.	No Choice	N	Δ_s	Perf.
SS=3, $\Delta_e=0.2$	0.35	4.58	0.06	3.5	0.58	33.6	0.25	0.28
SS=3, $\Delta_e=0.4$	0.51	4.69	0.02	3.25	0.48	20.8	0.51	0.49
SS=3, $\Delta_e=0.6$	0.55	4.53	0.01	4.22	0.43	12.6	0.64	0.54
SS=3, $\Delta_e=0.8$	0.92	4.74	0.004	4.5	0.06	36.8	0.81	0.92
SS=5, $\Delta_e=0.2$	0.35	4.57	0.04	4.06	0.608	65	0.252	0.31
SS=5, $\Delta_e=0.4$	0.51	4.69	0.02	3.25	0.48	47	0.51	0.49
SS=5, $\Delta_e=0.6$	0.56	4.53	0.002	4.3	0.42	35.6	0.65	0.56
SS=5, $\Delta_e=0.8$	0.93	4.75	0.01	3.66	0.05	69.3	0.811	0.91
SS=7, $\Delta_e=0.2$	0.35	4.51	0.058	3.70	0.58	103.1	0.28	0.29
SS=7, $\Delta_e=0.4$	0.52	4.63	0.02	3.16	0.46	77	0.518	0.50
SS=7, $\Delta_e=0.6$	0.57	4.77	0.008	3.86	0.419	49.46	0.658	0.56
SS=7, $\Delta_e=0.8$	0.9	4.74	0.002	2.5	0.09	97.33	0.824	0.89

Prediction 2 stated that Δ_e and N should also have a negative correlation. Fig 5.4 shows N values getting smaller as Δ_e values get larger except when $\Delta_s = 0.8$ for every set size. A 2-tailed Pearson Correlation test did not reveal any significant negative

correlation ($r=-0.689$, $p=0.311$). The previous analysis (Table 5.3, $\Delta_e=0.8$ row) didn't reveal any negative correlation between Δ_s and N , in fact the correlation even though not significant enough, had positive tendency. We conducted the correlation test again without the data belonging to $\Delta_s = 0.8$, this time the correlation was significantly negative ($r=-0.989$, $p=0.027$).

Table 5.3. One-sample t-test results for each Δ_e values showing correlations between N and Δ_s as stated in Prediction 1. $M(r(\Delta_s, N))$ signifies the mean of the 15 Pearson Correlation values obtained from each subject's trial-by-trial data. $M(\Delta_s)$ signifies the sampled contingency mean for all the subjects; $M(N)$ signifies the mean of sample size for all the subjects. The last two rows in the table refer to statistic t and p (significance) in the t-test. All t-tests are based on $df=14$.

	$\Delta_e = 0.2$	$\Delta_e = 0.4$	$\Delta_e = 0.6$	$\Delta_e = 0.8$
$M(r(\Delta_s, N))$	-0.23	-0.31	-0.19	0.07
$M(\Delta_s)$	0.26	0.503	0.65	0.81
$M(N)$	67.2	48.2	32.5	67
t	-8.41	-14.29	-15.141	5.892
p	0.01	0.02	0.01	0.061

In **Prediction 3**, we expected that the subjects would produce larger Δ_s than Δ_e . Combining Prediction 1,2,and 3 both Δ_s and Δ_e should have a negative correlation with N . Fig 5.5 shows that average Δ_s values are slightly larger then Δ_e values for each set size. A paired sample t-test showed that Δ_s values are significantly larger than Δ_e for all the Δ_e values ($t(11)=-5.461$, $p<0.001$, $d=1.57$).Table 5.4 shows the t-test results for each Δ_e value showing Δ_s values significantly larger than Δ_e values except when Δ_e is 0.8. According to SSA, the observer, seeking small samples produces clear evidence, which leads to $\Delta_s > \Delta_e$. In contrast, according to the standard statistical approach, the observer should seek large samples so as to obtain $\Delta_e \approx \Delta_s$ as in the case of $\Delta_e = 0.8$.

Table 5.4. Paired-sample *t*-test results comparing Δ_e and Δ_s values for Prediction 3. All *t*-tests are based on *df*=2.

	$\Delta_e = 0.2$	$\Delta_e = 0.4$	$\Delta_e = 0.6$	$\Delta_e = 0.8$
$M(\Delta_s)$	0.26	0.503	0.65	0.81
<i>t</i>	-6.265	-42.25	-9.475	-3.326
<i>p</i>	0.025	0.001	0.011	0.08

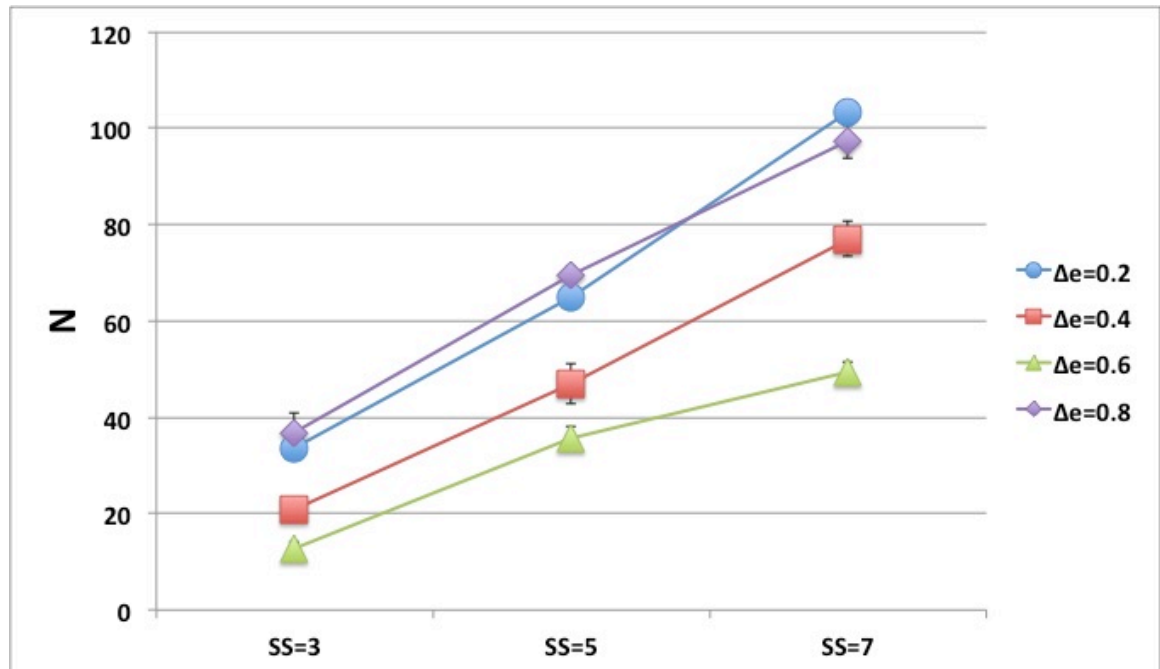


Fig 5.4. *N* values for different Δ_e values for each set sizes. For SSA cases, larger Δ_e values give smaller *N* values as stated in Prediction 2. Error bars signify $\pm$ standard errors.

In **Prediction 4**, a negative correlation between Confidence Ratings and *N* was expected. For each subject, we separated the trial-by-trial data with respect to Δ_e values to obtain the *N* vs. Confidence Ratings values. We calculated 2- tailed Pearson-Correlation tests giving 15 correlations values for each Δ_e values. We then compared the correlation values with 0 by performing one-sample *t*-tests for each Δ_e values. All correlations

between N and Confidence Ratings were significantly negative except when Δ_e was 0.8, indicating a significant small-sample advantage (See Table 5.5). Confidence Ratings vs. N for $\Delta_e=0.8$ case results were similar for Δ_s vs. N, or Δ_s not being greater to Δ_e case. $\Delta_e = 0.8$ case revealed a positive non-significant correlation between confidence ratings and sample size.

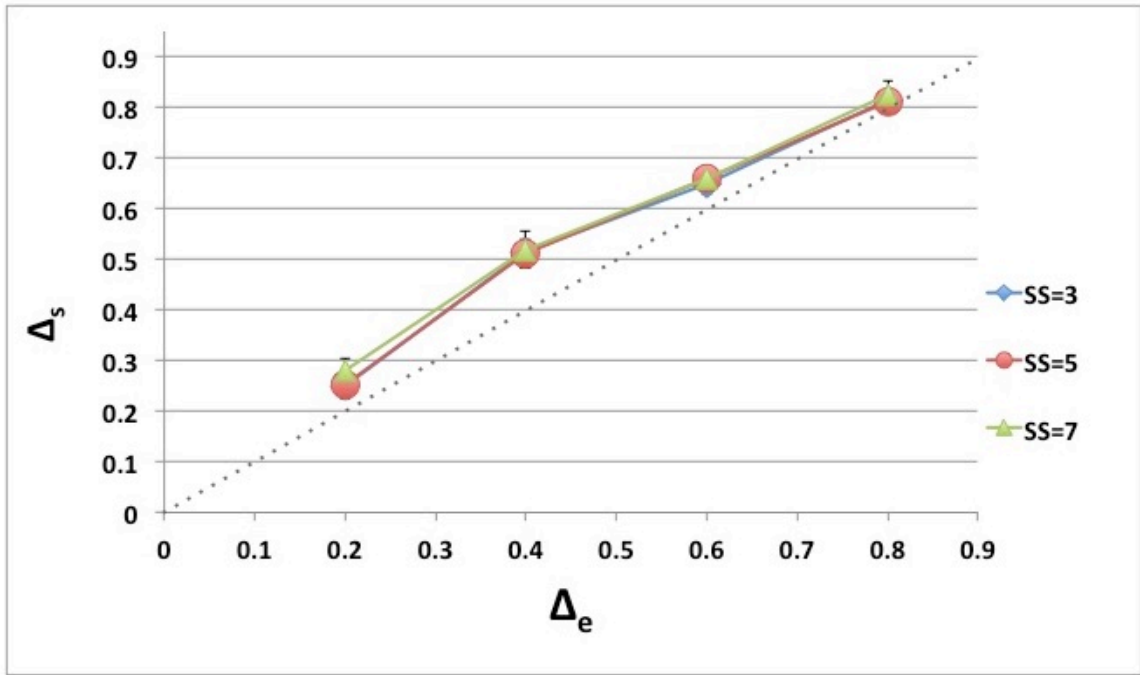


Fig 5.5. Δ_s vs. Δ_e values for different set sizes. Δ_s increases as Δ_e increases. The average Δ_s is larger than Δ_e . Δ_s values don't differ for different set sizes, it is independent of set-size. Error bars signify $\pm$ standard errors. Black dashed line shows the hypothetical scenario when Δ_s is equal to Δ_e .

In **Prediction 5**, a negative correlation was expected between Performance (Correct % - Incorrect %) and N. For each subject, we ran 2-tailed Pearson Correlation tests separating data corresponding to different Δ_e values. We compared the correlation coefficients with 0 using one sample t-test. Except the highest Δ_e , all correlations between N and Performance were significantly negative, indicating a significant small-sample

advantage (See Table 5.6). In Fig 5.6, Performance averaged across subjects for different Δ_e values is plotted for each set size. From low Δ_e values to the highest one, performance jumps from 29% to 90%. Performance rise with respect to an increase in the environmental contingency was expected whether the subject used small or large samples over his/her choices. The results for $\Delta_e = 0.8$ case show less than 10% No Choice decision, this indicates that subjects used a low threshold for their decision compared to $\Delta_e = 0.8$. Small sample advantage does not hold for low threshold values. A higher threshold value compared to Δ_e is required for small sample advantage observation.

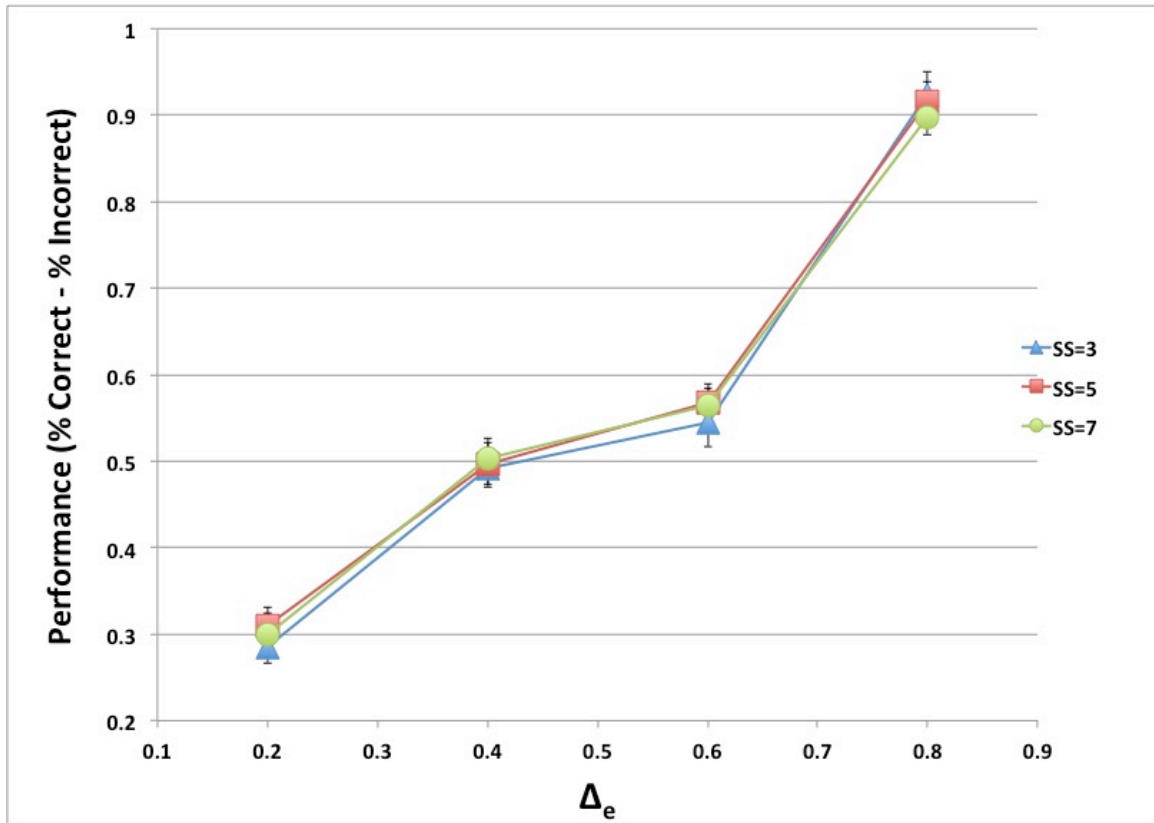


Fig 5.6. Performance values for different Δ_e values for each set size, it is independent of set-size. Error bars signify $\pm$ standard errors.

Table 5.5. 2-tailed t-test results for Δ_e values (0.2, 0.4, 0.6) showing correlations between N and Confidence Ratings as stated in Prediction 4. $M(r(CR, N))$ signifies the mean of the 15 Pearson Correlation values obtained from each subject's trial-by-trial data. All t-tests are based on $df=14$.

	$\Delta_e = 0.2$	$\Delta_e = 0.4$	$\Delta_e = 0.6$	$\Delta_e = 0.8$
M(r(CR, N))	-0.21	-0.34	-0.17	0.12
M (CR)	3.81	4.02	4.21	4.6121
M (N)	67.2	48.2	32.5	67
t	-3.121	-5.902	-8.44	2.63
p	0.022	0.003	0.048	0.072

Table 5.6. 2-tailed t-test results for Δ_e values showing correlations between N and Performance as stated in Prediction 5. $M(r(P, N))$ signifies the mean of the 15 Pearson Correlation values obtained from each subject's trial-by-trial data. All t-tests are based on $df=14$.

	$\Delta_e = 0.2$	$\Delta_e = 0.4$	$\Delta_e = 0.6$	$\Delta_e = 0.8$
M(r(P, N))	-0.16	-0.25	-0.21	0.04
M (P)	0.296	0.504	0.552	0.906
M (N)	67.2	48.2	32.5	67
t	-4.57	-8.062	-5.21	1.32
p	0.024	0.005	0.039	0.135

5.5. Experiment 5.2: Heterogeneous Displays

We created heterogeneous displays in order to study the relation between sample size and fixation behavior. The main difference between the homogeneous and heterogeneous displays is that the number of items in fixation windows (set size) can be different (see Fig 5.3 b). The size of each Gaussian window would give a hint about its items inside it. Because the natural environment doesn't have a fixed uniform information distribution, the heterogeneous display condition is closer to natural settings

compared to homogeneous display part. In this experiment, subjects were able to decide whether to add a larger or smaller sample size to their ongoing sampling processes. The preference of the subjects was determined directly during the sampling process in the heterogeneous display experiment. We tested the 5 predictions mentioned above in the homogeneous display experiment. In addition to the homogeneous display results, in the heterogeneous display experiment we tested SSA theory both spatially (by the number of items in the fixation window) and temporally (by the number of fixations) by the 5 previous predictions and 2 additional predictions mentioned below.

Prediction 6: When Δ_e is low, the more items there are in the fixation window, the more fixations the observer will make. In other words, providing more information at each fixation will cause the observer to sample more by an increased number of fixations.

Prediction 7: states that observers will scan the stimulus so as to select fixation windows with smaller samples.

5.5.1. Procedure

The procedure was identical to the Exp. 5.1 with only one difference: instead of homogeneous display, we had the heterogeneous display (see Fig 5.3 b). The circles contouring the gray Gaussian envelopes did not have the same diameters; hence there wasn't a fixed set size like in the 1st part of the experiment but had four different contingency values (0.2, 0.4, 0.6, or 0.8). The four different contingency values were mixed equally in each block. Not having a fixed set-size made the environment more natural. Each subject had 720 trials making 10800 trials for all the subjects.

5.5.2. Results and Discussion

Similar to the homogeneous display part, each trial produced N, Correct/ Incorrect/ No Choice answer, number of fixations, their order and duration, confidence rating, Δ_s , and percentage of choices for different set sizes. Table 5.7 shows the whole averaged data over 15 subjects. For every trial, 6 Gaussian windows were created for each set size making a total of 18 Gaussian windows. In terms of sample size, 6 Gaussian windows made 18 items for set-size 3, 30 items for set-size 5, and 42 items for set-size 7 making a total of 75 items for each trial.

As conducted in the homogeneous display experiment, we analyzed the data with respect to the 7 predictions cited in the previous sections. In **Prediction 1**, a negative correlation between N and Δ_s was expected. For each subject, we separated the trial-by-trial data with respect to Δ_e values to obtain the N vs. Δ_s values. We calculated 2- tailed Pearson-Correlation tests giving 15 correlations values for each Δ_e values. We then compared the correlation values with 0 by performing one-sample t-tests for each Δ_e values. All correlations between N and Δ_s were significantly negative except when Δ_e was equal to 0.8, indicating a significant small-sample advantage for the remaining contingency values (See Table 5.8). The case of $\Delta_e = 0.8$ was discussed in the homogeneous display results. Due to its positive extremity, the broad distribution of small sample is not advantageous. In this case $\Delta_e = \Delta_s$.

Prediction 2 stated that Δ_e and N should also have a negative correlation. Tables 5.7 & 5.8 show N values getting smaller as Δ_e values get larger except when $\Delta_s = 0.8$ for every set size. A 2-tailed Pearson Correlation test didn't reveal any significant negative correlation ($r = -0.524$, $p = 0.081$). The previous analysis (Table 5.8, $\Delta_e = 0.8$ row) didn't

reveal any negative correlation between Δ_s and N , in fact the correlation even though not significant enough, had positive tendency. We conducted the correlation test again without the data belonging to $\Delta_s = 0.8$, this time the correlation was significantly negative ($r = -0.772, p = 0.034$).

Table 5.7. For each Δ_e value from left to right: correct percentage, correct confidence level, incorrect percentage, incorrect confidence level, no choice percentage, sample size (N), Δ_s , performance percentage (correct percentage – incorrect percentage), and subjects' choices for each set size in percentages are reported for the heterogeneous display.

Δ_e	Crrct	Conf.	Incrrect	Conf.	N.C.	N	Δ_s	Perf.	SS=3	SS=5	SS=7
0.2	0.32	4.41	0.05	3.1	0.63	51.1	0.26	0.27	44	32	24
0.4	0.54	4.52	0.04	3.2	0.41	44.7	0.53	0.5	48	30	22
0.6	0.58	4.55	0.01	4.1	0.40	34.2	0.71	0.57	45	34	21
0.8	0.91	4.82	0.001	4.11	0.08	66.8	0.8	0.91	33	33	34

Table 5.8. One-sample t -test results for each Δ_e values showing correlations between N and Δ_s as stated in Prediction 1. $M(r(\Delta_s, N))$ signifies the mean of the 15 Pearson Correlation values obtained from each subject's trial-by-trial data. $M(\Delta_s)$ signifies the sampled contingency mean for all the subjects; $M(N)$ signifies the mean of sample size for all the subjects. The last two rows in the table refer to statistic t and p (significance) in the t -test. All t -tests are based on $df = 14$.

	$\Delta_e = 0.2$	$\Delta_e = 0.4$	$\Delta_e = 0.6$	$\Delta_e = 0.8$
$M(r(\Delta_s, N))$	-0.19	-0.22	-0.21	0.11
$M(\Delta_s)$	0.26	0.53	0.71	0.8
$M(N)$	51.1	44.7	34.2	66.8
t	-6.13	-5.97	-9.22	2.49
p	0.02	0.01	0.01	0.068

Prediction 3 predicted that Δ_s would be larger than Δ_e . When combined, Predictions 1,2,and 3 state that both Δ_s and Δ_e are supposed to have negative correlation with the sample size N. Tables 5.7 & 5.8 show that Δ_s values are slightly larger then Δ_e values for each Δ_e value except 0.8. A paired sample t-test revealed that the difference between Δ_s values and Δ_e for all the Δ_e values are not significant ($t(3)=-2.585$, $p=0.081$, $d=17.24$). Considering the results obtained from homogeneous displays and Predictions 1 & 2, we conducted t-test again without $\Delta_e = 0.8$ values, this time the difference was significantly larger ($t(3)=-4.804$, $p=0.04$, $d=2.77$). According to SSA, the observers seeking small samples produces clear evidence, which leads to $\Delta_s > \Delta_e$. In contrast, according to the standard statistical approach, the observer should seek large samples so as to obtain $\Delta_e \approx \Delta_s$ as in the case of $\Delta_e = 0.8$. Additionally we conducted paired sample t-tests comparing the environmental contingency to the sampled contingency on subject level. Table 5.9 shows the results for the t-tests showing the significant difference for all the Δ_e values except 0.8.

Table 5.9. Paired-sample t-test results comparing Δ_e and Δ_s values for Prediction 3. All t-tests are based on $df=14$.

	$\Delta_e = 0.2$	$\Delta_e = 0.4$	$\Delta_e = 0.6$	$\Delta_e = 0.8$
M(Δ_s)	0.26	0.53	0.71	0.8
t	-4.675	-17.341	-7.32	-1.61
p	0.01	0.01	0.017	0.094

In **Prediction 4**, a negative correlation between Confidence Ratings and N was expected. For each subject, we separated the trial-by-trial data with respect to Δ_e values to obtain the N vs. Confidence Ratings values. We conducted 2-tailed Pearson-Correlation

tests for each subject's each Δ_e values, following the tests, we performed one sample t-tests for each Δ_e value. The correlations revealed significant negative correlations between N and Confidence Ratings except when Δ_e was 0.8 (see Table 5.10).

Table 5.10. One-sample t-test results for Δ_e values showing correlations between N and Confidence Ratings as stated in Prediction 4 for the heterogeneous display. $M(r(CR, N))$ signifies the mean of the 15 Pearson Correlation values obtained from each subject's trial-by-trial data. All t-tests are based on $df=14$.

	$\Delta_e = 0.2$	$\Delta_e = 0.4$	$\Delta_e = 0.6$	$\Delta_e = 0.8$
M(r(CR, N))	-0.27	-0.31	-0.21	0.2
M (CR)	4.41	4.52	4.55	4.82
M (N)	51.1	44.7	34.2	66.8
t	-5.24	-4.97	-6.31	-0.17
p	0.019	0.023	0.039	0.069

Prediction 5 stated that a negative correlation was expected between Performance (Correct % - Incorrect %) and N. For each subject, we ran 2-tailed Pearson Correlation tests separating data corresponding to different Δ_e values. We compared the correlation coefficients with 0 using one sample t-test. Except the highest Δ_e , all correlations between N and Performance were significantly negative, indicating a significant small-sample advantage (See Table 5.11).

The performance jumped from 0.27 to 0.91 from $\Delta_e=0.2$ to $\Delta_e=0.8$. For the highest environment contingency the “No Choice” percentage is only 8% indicating that subjects used a low threshold for their decision, and this is the reason we don't see any small sample advantage in this condition.

Table 5.11. One-sample *t*-test results for Δ_e values showing correlations between *N* and Performance as stated in Prediction 5. *M* (*r*(*P*, *N*)) signifies the mean of the 15 Pearson Correlation values obtained from each subject's trial-by-trial data. All *t*-tests are based on *df*=14.

	$\Delta_e = 0.2$	$\Delta_e = 0.4$	$\Delta_e = 0.6$	$\Delta_e = 0.8$
M(r(P, N))	-0.11	-0.19	-0.14	0.12
M (P)	0.27	0.5	0.57	0.91
M (N)	51.1	44.7	34.2	66.8
t	-6.41	-5.029	-11.48	3.43
p	0.041	0.037	0.046	0.072

Prediction 6 stated that for low Δ_e values, the more items there are in the fixation window, the more fixations the observer will make. In other words, providing more information at each fixation will cause the observer to sample more by an increased number of fixations. For each subject, we have divided the sampled fixations into first part (first 3 fixations) and second part (the remaining fixations). If the first sampled part's average number of set size is between 3-5, in other words if the subject preferred smaller set sizes in his/her first part, then we called that as small set size preference (SSSP). The opposite case was called large set size preference (LSSP) for an average number between 5-7. We predicted that if the subjects started their sampling with smaller set sizes, they would stop sampling with less fixations compared to the subjects starting with bigger set sizes. We expected that subjects starting with SSSP would make fewer fixations compared to subjects starting with LSSP. For $\Delta_e=0.2$, 9 out of 15 subjects preferred SSSP with an average of 6 fixations windows used compared to 6 subjects preferring LSSP with an average of 16 fixations windows. For $\Delta_e=0.4$, 8 out of 15 subjects preferred SSSP with an average of 5 fixations windows used compared to 7 subjects preferring LSSP

with an average of 13 fixations windows. For $\Delta_e=0.6$, 8 out of 15 subjects preferred SSSP with an average of 5 fixations windows used compared to 7 subjects preferring LSSP with an average of 9 fixations windows. For $\Delta_e=0.8$, 5 out of 15 subjects preferred SSSP with an average of 11 fixations windows used compared to 10 subjects preferring LSSP with an average of 15 fixations windows. All the fixation window values are for the whole block (1st part + 2nd part).

Prediction 7 stated that observers would scan the stimulus so as to select fixation windows with smaller samples. Fixation window radius was in positive correlation with the inside sample size. In other words, a fixation window containing 7 samples has a larger radius compared to a fixation window with 5 or 3 samples. The subjects were expected to understand this concept after few trials in the beginning of the training. On average, subjects' choices were 74.75% on smaller sampled fixation windows containing 3 or 5 samples whereas all 3 set size fixation windows were distributed equally in terms of quantity (33.3% for each of them). Table 5.7 shows the choice distribution for different set sizes for each Δ_e values. Set size 7 was the least preferred over the subjects except for the largest environment contingency. When $\Delta_e = 0.8$, the choice was balanced over the 3 set sizes.

The results obtained from the predictions were not fully conclusive. Although we were expecting SSA not holding for large Δ_e values and that we found it in the case of $\Delta_e = 0.8$, since we did not know t used by the subjects, we could not establish directly which of the scenarios depicted in Fig 5.2 was in play. Fig 5.2 depicts the model for the small sample advantage theory, but even though several Δ_e values seems to provide small sample advantage, the percentage values in Table 5.2 contradicts them. Additionally, in

order for a small sample advantage, the decision threshold t needs to be higher than the sampled contingency Δ_s , and sampled contingency Δ_s needs to be higher than the environment contingency Δ_e . Considering that the distribution is centered at Δ_e , this would imply that, under SSA, the percentage correct could never exceed 50%, if one considers the probability density functions. However, in the experiment, we have a realization of the random variable and it is possible to exceed 50%, based on the number of trials actually received by the subjects. To address these questions, we applied the proposed decision rule to actual trials in the experiments and obtained estimates of t from the simulations. For all the subjects, we combined all the set sizes as well as all the Δ_e values. The rule to classify a trial was based on the model explained in Fig 5.2. Correct and Incorrect corresponded to the areas under $\Delta_s > t$ & $\Delta_s < -t$ respectively for positive Δ_e values. It was the other way around for trials with negative Δ_e values. The region $-t < \Delta_s < t$ corresponded to no Choice. We ran the simulation from $t = 0.1$ to $t = 0.9$ with a step size of 0.01. To obtain an estimate, we implemented an error formula, and we picked the threshold minimizing the error. The formula was given in this equation:

$$\text{Error}(t) = (C_t - C)^2 + (I_t - I)^2 + (NC_t - NC)^2, \quad (\text{Eq. 5.2})$$

where C , I , NC were number of correct, incorrect, and no choice trials respectively obtained empirically, and C_t , I_t , and NC_t were correct, incorrect, and no choice values according to the simulation with respect to the threshold value ranging from 0.1 to 0.9 with a step size of 0.01. When all the set sizes were combined along with 4 different Δ_e values, subjects produced 6377 correct trials, 4026 no choice trials and 397 incorrect trials. A threshold value of 0.39 gave the minimum error value of 536 (0.049 %) with 6373 correct, 4012 no choice and 415 incorrect trials (See Table 5.12 & Appendix A).

We ran a second simulation to “fine-tune” the threshold used by the subjects. The step size was decreased from 0.01 to 0.001. The threshold range was from 0.3 to 0.5. The error value decreased from 536 to 494 (from 0.049 % to 0.045 %) with a threshold value of 0.391 (See Table 5.13 & Appendix-B). A threshold value of 0.391 corresponded to 6360 correct, 4029 no choice and 411 incorrect trials. The simulation results revealed that subjects used a threshold value of 0.391. Because all the Δ_e values were intermixed within blocks throughout the experiments, it is likely that subjects used the same threshold for all Δ_e values.

Table 5.12. Simulation results for threshold values between 0.1 and 0.9 with a step size of 0.01. The complete table is given in Appendix A. The row with the yellow highlight shows t for which the error is minimum.

Threshold	Correct	No choice	Incorrect	Error	Error %
0.3	7071	2952	777	1779512	164.7696296
0.31	7024	3044	732	1495158	138.4405556
0.32	6968	3150	682	1197882	110.915
0.33	6921	3250	629	951936	88.14222222
0.34	6866	3353	581	725906	67.21351852
0.35	6816	3457	527	533382	49.38722222
0.36	6711	3591	498	310982	28.79462963
0.37	6613	3713	474	159594	14.77722222
0.38	6496	3854	450	46554	4.310555556
0.39	6373	4012	415	536	0.04962963
0.4	6270	4149	381	26834	2.48462963
0.41	6135	4302	363	135896	12.58296296
0.42	6014	4447	339	312374	28.92351852
0.43	5875	4605	320	593174	54.92351852
0.44	5756	4752	292	923742	85.53166667
0.45	5643	4883	274	1288334	119.2901852
0.46	5537	5009	254	1692338	156.697963
0.47	5456	5122	222	2080082	192.6001852
0.48	5369	5219	212	2473538	229.0312963
0.49	5313	5296	191	2787432	258.0955556
0.5	5226	5408	166	3288086	304.4524074

Table 5.13. Simulation results for threshold values between 0.3 and 0.5 with a step size of 0.001. The complete table is given in Appendix B. The row with the yellow highlight shows t for which the error is minimum.

Threshold	Correct	No choice	Incorrect	Error	Error %
0.38	6496	3854	450	46554	4.310555556
0.381	6487	3866	447	40200	3.722222222
0.382	6471	3885	444	30926	2.863518519
0.383	6449	3911	440	20258	1.875740741
0.384	6435	3928	437	14568	1.348888889
0.385	6424	3942	434	10634	0.98462963
0.386	6411	3961	428	6342	0.587222222
0.387	6401	3972	427	4392	0.406666667
0.388	6392	3986	422	2450	0.226851852
0.389	6383	3997	420	1406	0.130185185
0.39	6373	4012	415	536	0.04962963
0.391	6360	4029	411	494	0.045740741
0.392	6352	4042	406	962	0.089074074
0.393	6341	4054	405	2144	0.198518519
0.394	6334	4064	402	3318	0.307222222
0.395	6327	4074	399	4808	0.445185185
0.396	6307	4097	396	9942	0.920555556
0.397	6296	4113	391	14166	1.311666667
0.398	6288	4127	385	18266	1.691296296
0.399	6280	4137	383	21926	2.030185185
0.4	6270	4149	381	26834	2.48462963

5.6. General Discussion

In this study, our goal was to investigate how decisional processes sample information before making a decision. From an evolutionary perspective, humans are active explorers and it is crucial to understand how we collect information from the environment and how we use this information to make decisions or to learn about our environment. Small sample advantage theory described a challenging theory that contingencies might be more detectable from small than large samples of observations. Specifically, we tested our predictions of the Small Sample Advantage theory, according

to which decision processes keep sample size small to increase the probability of detecting stimulus contingencies. Obtained contingency was always higher than the environment contingency. Because small samples made clearer indications, subjects' confidence ratings were higher in smaller number of samples. In contrast with traditional statistical theory, small samples gave higher performance levels compared to large samples. As we said earlier, only under clear boundary conditions, subjects tend to prefer smaller samples with higher confidence ratings. Based on SSA theory, the percentage correct could never reach 50%, however in practice, observers received limited samples and theoretical distributions are valid only asymptotically when the number of trials goes to infinity.

Our results are obtained in a way that we overcome two challenging limitations in testing SSA. First, we introduced self-guided exploration resulting our sample size (N) to correspond to the actually used sample size. Second, we established a natural scanning behavior by controlling eye movements and by allowing the subjects “actively” inspect. Our study provided further support for the SSA theory. It is in direct conflict with the present state of sample size decision understanding. The theory behind small sample advantage challenges the current status quo and offers an alternative way of understanding information sampling.

In terms of an evolutionary perspective, using small samples over large samples has benefits in survival. It might be considered as an augmented ability to detect several environmental contingencies. In nature, a more limited short-term memory might be an advantage instead of a liability (Heinrich, 1979; McNamara & Houston, 1985, 1987; Shafir & Roughgarden, 1998).

Chapter 6. Summary

The purpose of this study was to investigate how attentional and decisional processes select visual inputs for further processing. Our long-term goal was to understand the functional mechanisms creating the perceptual and cognitive operations under dynamic ecological conditions. The study was divided into three specific aims. The first and second specific aims were about visual attention and the last part was focused on decisional processes. Specific aim 1 was to investigate the dynamics of how attention was allocated to perceptual groups, in particular to understand how attentional allocation took place during formation and dissolution of perceptual groups. Specific aim 2 was to investigate whether exogenous and endogenous attention operated independently or through interactions. Specific aim 3 was to test the hypothesis that small samples lead to better decisions than large samples for detecting stimulus contingencies during self guided exploration.

For the first specific aim, we examined object-based attentional facilitation while varying the relative timing between the appearance of the cue and the formation (or dissolution) of perceptual groups over two experiments. Using direction of motion, we separated objects into two distinct groups. Even though our previous study investigated the relationship between attention and perceptual grouping, this was done only for steady state, and in nature perceptual groups spontaneously form and dissolve. In this part of our study, we addressed the issue into a more ecological setting. Results showed that attentional advantage was observed during both formation and dissolution of perceptual groups. We are not able to clarify the timing of the brain for cue processing and attention

but even though we do not know the exact time when the cue is processed in the brain, it is still possible to compare the data of the group formation and group dissolution experiments.

For the second aim, we investigated the relationship between exogenous and endogenous attention, in particular the interactions between them by using both peripheral and central cues. We examined the topic with an experimental design considering task types (detection, discrimination), cue validity (valid, invalid within, invalid between, catch), and stimulus mobility (static, dynamic). The results show that detection tasks require significantly less time compared to dynamic tasks. We observed significant interactions between endogenous and exogenous orienting of attention when the task was discrimination. Although not significant, there was a similar interaction tendency when the task was detection. The interaction between endogenous and exogenous attention depended on the validity of both cues. A valid endogenous cue weakened the strength of the exogenous cue making the endogenous cue more dominant than the exogenous cue. We concluded that interactions between endogenous and exogenous orienting mechanisms are similar for static and dynamic stimuli and these interactions depend on task demands and the reliability of cues.

For the third aim, we investigated how decisional processes sample information before making a decision. Our goal was to understand how perceptual and cognitive processes operate in real-time in a natural dynamic scene. We conducted two experiments to test the small sample advantage theory for detecting stimulus contingencies under self-guided exploration. Our results show that sampled contingency was higher than the environmental contingency. As expected in a small sampled environment, subjects'

confidence ratings were high. The high percentages of no choice were observed which are indispensable for small sample usage. We concluded our findings that small samples led to better decisions than large samples for detecting stimulus contingencies for low Δ_c values. Based on the empirical sampling contingency and model decision rules, we conducted simulations to determine the threshold value used by the subjects. The measured threshold value can be misleading due to the fact that any theoretical distribution is valid only at its asymptote when the number of trials goes to infinity. We calculated the threshold value based on subjects' sampling contingency.

6.1. Future Work

In the first specific aim, we conducted the experiment using motion grouping for both perceptual group formation and dissolution. The study's results are based on one type of Gestalt principle. Different principles' effects were not compared in a study. Our study can be replicated using color grouping instead of motion grouping. Instead of all the disks having blue color, they can change colors up to a certain point and then can be grouped by color for a brief moment. The color grouping effect on attention and the interaction between attention and perceptual grouping can be studied. Another idea can be picked from our own results, the reasons behind different time courses for group formation and dissolution can be studied in a much more detail focusing more in the $COA_G=0$ region perhaps with more than one cue duration.

In the second aim, we implemented the experiment to study interactions between exogenous and endogenous attention using double cuing paradigm. To our knowledge,

this was the only study using the same paradigm for both detection and discrimination tasks as well as for static and dynamic stimuli. This study can be combined with an imaging study to further analyze the matter. The main problem with this approach might be the lack of temporal resolution for the exogenous attention. The fMRI technique is not fast enough to capture the changes caused by the exogenous attention. The imaging techniques such as EEG (for temporal resolution) and fMRI (for spatial resolution) need to be combined to study both types of attention. Both temporal and spatial resolution becomes equally important studying their interactions. Several other imaging techniques such as ERP are used in attention studies but due to the fact that every paradigm's result is very different than each other. A more complete paradigm such as ours can be used on all of these techniques mentioned. Even though we proved that there is indeed interaction between exogenous attention and endogenous attention, a more broad study is required to identify the details of this interaction including the responsible brain regions.

In our last aim, we tested the hypothesis that small samples lead to better decisions than large samples for detecting stimulus contingencies during self-guided exploration. The experiments that we conducted might be used to build a computational model for small sample advantage theory, and to test it against the empirical data. The model can have several stages for important cognitive processes such as attention and working memory. Parameters required for this model can be obtained through empirical methods as we measured the threshold used by the subjects. In the experiment we started with the environmental contingency and through that we obtained sampled contingency, by developing this model, we can obtain a good estimate of contingency in cognitive representation. Another empirical idea is that instead of a more “discrete” approach, a

new study can focus on low environmental contingency values to determine a function of small sample advantage vs. environmental contingency. Also to test SSA, we used two different colored rectangles; the paradigm can be even more simplified to reduce fatigue. The main challenge in data collection was to maintain the comfort level of the subjects due to eye tracking. The focus can be to decrease the time by maintaining the number of trials perhaps by offering even less items. This can be done either by reducing the set size values (to 2-3-4) or reducing the total number of fixation windows for each set size. Another method to make the experiment “less tiring” can perhaps to use different shapes instead of presenting the same shapes vertically and horizontally.

References

Abrams, R. A., & Dobkin, R. S. (1994). "Inhibition of Return: Effects of Attentional Cuing on Eye Movement Latencies." *Journal of Experimental Psychology: Human Perception & Performance*, 20, 467- 477.

Abrams, R. A., & Law, M. B. (2000). "Object-Based Visual Attention with Endogenous Orienting." *Perception and Psychophysics*, 62, 818-833.

Avrahami, J. (1999). "Object of Attention, Objects of Perception." *Perception & Psychophysics*, 61, 1604–1612. doi:10.3758/BF03213121

Boi, M., Vergeer, M., Ogmen, H., & Herzog, M. H. (2011). "Nonretinotopic Exogenous Attention." *Current Biology*, 21, 1732– 1737. doi:10.1016/j.cub.2011.08.059.

Bollmann M. (1999). "Entwicklung einer Aufmerksamkeitssteuerung fuer ein aktives Sehsystem." PhD thesis, Department of Computer Science, University of Hamburg.

Behrmann, M., & Tipper, S. P. (1999). "Attention Accesses Multiple References Frames: Evidence from Unilateral Neglect." *Journal of Experimental Psychology: Human Perception and Performance*, 25, 83–101.

Berger A & Avishai H., Rafal R. (2005) "Competition Between Endogenous and Exogenous Orienting of Visual Attention." *Journal of Experimental Psychology: General*, 134, No 2, 207-221.

Broadbent, D. E. (1958). Perception and Communication. London: Pergamon Press.

Brown, J. M., Breitmeyer, B. G., Leighty, K. A., & Denney, H. I. (2006). "The Path of Visual Attention." *Acta Psychologica*, 121, 199–209.

Borges, B., Goldstein, D. G., Ortmann, A., & Gigerenzer, G. (1999). Can Ignorance Beat the Stock Market? Simple Heuristics that Make Us Smart (pp. 59–72). Oxford: Oxford University Press.

Boucart M., A.M. Hena, and C. Belin. Vision: Aspects Perceptifs et Cognitifs. Edition Solal, 1998.

Busse, L., Katzner, S., & Treue, S. (2008). "Temporal Dynamics of Neuronal Modulation During Exogenous and Endogenous Shifts of Visual Attention in Macaque Area MT." *Proceedings of the National Academy of Sciences of the USA*, 105(42), 16380–16385.

Cahan, S. (2010). "Decision Quality (always) Always Increases with the Size of Information Samples – Provided that the Decision Rule is Statistically Valid: Comment on Fiedler and Kareev (2006)." *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 36, 829-841.

Carey, S., & Xu, F. (2001). "Infant Knowledge of Objects: Beyond Object Files and Object Tracking." *Cognition*, 80, 179-213.

Carrasco, M. (2011) "Visual attention: The Past 25 Years." *Vision Research*, 51, pp. 1484-1525.

Cheal, M., & Lyon, D. R. (1991). "Central and Peripheral Precuing of Forced-Choice Discrimination." *Quarterly Journal of Experimental Psychology*, 43A, 859–880. doi:10.1080/14640749108400960

Chen, Z. (2012). "Object-Based Attention: A Tutorial Review." *Attention, Perception, & Psychophysics*, 74, 784–802.

Chica, A.B., Bartolomeo, P., & Lupiáñez, J. (2013). "Two Cognitive and Neural Systems for Endogenous and Exogenous Spatial Attention." *Behavioral Brain Research*. 237: 107–123.

Chica, A.B., Lupiáñez, J., & Bartolomeo, P. (2006). "Dissociating Inhibition of Return from the Endogenous Orienting of Spatial Attention: Task Set Modulation". *Cognitive Neuropsychology*, 23(7), 1015-1034.

Chica, A.B., Sanabria, D., Lupiáñez, J., & Spence, C. (2007). "Comparing Intramodal and Crossmodal Cuing in the Endogenous Orienting of Spatial Attention." *Experimental Brain Research*, 179(3), 353-364.

Chica A.B., Charras P, Lupiáñez J. (2008). "Endogenous Attention and Illusory Line Motion Depend on Task Set." *Vision Research*; 48(21):2251–9.

Christ, S.E., McCrae C.S., Abrams R.A., (2002). "Inhibition of Return in Static and Dynamic displays." *Psychonomic Bulletin & Review*, 9, 80-85.

Corbetta M, Miezin FM, Shulman GL, Petersen SE. (1993). "A PET Study of Visuospatial Attention." *The Journal of Neuroscience*; 13(3): 1202–26.

Corbetta M., Shulman GL (2002) “Control of Goal-directed and Stimulus-Driven Attention in the Brain.” *Nat Rev Neurosci* 3:201–215.

Corbetta M, Patel G, Shulman GL. (2008). “The Reorienting System of the Human Brain: from Environment to Theory of Mind.” *Neuron*; 58(3):306–24.

Damasio, Antonio R. (1994). Descartes' Error: Emotion, Reason, and the Human Brain. New York: Putnam.

Danckert J., Maruff P, Crowe S, Currie J (1998) “Inhibitory Processes in Covert Orienting in Patients with Alzheimer’s Disease.” *Neuropsychology* 12:225–241.

Desimone R, M. Wessinger, L. Thomas, and W. Schneider. (1990). “Attentional Control of Visual Perception: Cortical and Subcortical Mechanisms.” *Cold Spring Harbor on Quantitative Biology, Vol. LV: The Brain, Cold Spring Harbor Laboratory Press*, pp. 963-971.

Deutsch, J. A., & Deutsch, D. (1963). “Attention: Some Theoretical Considerations.” *Psychological Review*, 70, 80–90.

Dodd, M. D., & Pratt, J. (2005). “Allocating Visual Attention to Grouped Objects.” *European Journal of Cognitive Psychology*, 17, 481-497.

Duncan, J. (1984). “Selective Attention and the Organization of Visual Information.” *Journal of Experimental Psychology: General*, 113, 501–517.

Egeth, H. E., & Yantis, S. (1997). “Visual Attention: Control, Representation, and Time Course.” *Annual Review of Psychology*, 48, 269–297. doi:10.1146/.48.1.269

Egley, R., Driver, J., & Rafal, R. D. (1994a). "Shifting Visual Attention between Objects and Locations: Evidence from Normal and Parietal Lesion Participants." *Journal of Experimental Psychology: General*, 123, 161-177.

Egley, R., Rafal, R., Driver, J., & Starrveld, Y. (1994b). "Covert Orienting in the Split-Brain Reveals Hemispheric Specialization for Object-Based Attention." *Psychological Science*, 5, 380-383.

Elman, J. L. (1993). "Learning and Development in Neural Networks: The Importance of Staring Small." *Cognition*, 48, 71-99.

Eriksen, B. A., & Eriksen, C.W. (1974). "Effects of Noise Letters Upon the Identification of a Target Letter in a Nonsearch Task." *Perception & Psychophysics*, 16, 143-149.

Eriksen, C. W., & Hoffman, J. E. (1973). "The Extent of Processing of Noise Elements During Selective Encoding From Visual Displays." *Perception & Psychophysics*, 14, 155-160.

Eriksen, C. W., & St. James, J. (1986). "Visual Attention Within and Around the Field of Focal Attention: A Zoom Lens Model." *Perception & Psychophysics*, 40, 225-240.

Eriksen, C. W., & Yeh, Y. -Y. (1985). "Allocation of Attention in the Visual Field." *Journal of Experimental Psychology: Human Perception and Performance*, 11(5), 583-597.

Evans, L., & Buehner, M. J. (2011). "Small Samples Do Not Cause Greater Accuracy-But Clear Data May Cause Small Samples: Comment on Fiedler and Kareev (2006)." *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 37, 792-799.

Fiedler, K., & Kareev, Y. (2006). "Does Decision Quality (always) Increase with the Size of Information Samples? Some Vicissitudes in Applying the Law of Large Numbers." *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 32, 883-903.

Fiedler, K., & Kareev, Y. (2011). "Clarifying the Advantage of Small Samples: As It Relates to Statistical Wisdom and Cahan's (2010) Normative Intuitions." *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 37, 1039-1043.

Gibson, B. S., & Egeth, H. (1994). "Inhibition of Return to Object-Based and Environment Based Locations." *Perception & Psychophysics*, 55, 323-339. Doi: 10.3758/BF03207603.

Gigerenzer, G., & Goldstein, D. G. (1996). "Betting on One Good Reason: The Take the Best Heuristic. Simple Heuristics that Make Us Smart' (pp. 75-96). *New York: Oxford University Press*.

Gitelman, D.R., Nobre, A.C., Parrish, T.B., LaBar, K.S., Kim, Y.H., Meyer, J.R., et al. "A Large-Scale Distributed Network for Covert Spatial Attention: Further Anatomical Delineation Based on Stringent Behavioral and Cognitive Controls." *Brain* 1999; 122(6):1093-106.

Godijn, R., Theeuwes, J. (2002). "Programming of Endogenous and Exogenous Saccades: Evidence for a Competitive Integration Model." *Journal of Experimental Psychology: Human Perception and Performance*; 28(5): 1039–54.

Gold, Joshua I.; Shadlen, Michael N. (2007). "The Neural Basis of Decision Making." *Annual Review of Neuroscience*. 30: 535–574. doi:10. 1146 /annurev.neuro. 29.051605.113038.

Goldstein, D. G., & Gigerenzer, G. (2002). "Models of Ecological Rationality: The Recognition Heuristic." *Psychological Review*, 109, 75-90.

Gonen, F.F. & Ogmen, H. (2016). "Exogenous Attention During Perceptual Group Formation and Dissolution." *Attention Perception Psychophysics* doi:10.3758/s13414-016-1235-z

Gonen, F.F., H. Hallal, H. Ogmen, (2014). "Facilitation by Exogenous Attention for Static and Dynamic Gestalt Groups." *Attention, Perception & Psychophysics*, vol. 76, pp. 1709-1720.

Gonen, F.F. (2013), Master of Science Thesis, "Effects of Distance and Grouping on Visual Attention for Static and Dynamic Displays." University of Houston

Griffin, D., & Tversky, A. (1992). "The Weighting of Evidence and the Determinants of Confidence." *Cognitive Psychology*, 24, 411-435.

Grubb, M. A., White, A. L., Heeger, D. J., & Carrasco, M. (2015). "Interactions Between Voluntary and Involuntary Attention Modulate the Quality and Temporal Dynamics of Visual Processing." *Psychonomic Bulletin & Review*, 22, 437–444.

Han, S., Humphreys, G. W., & Chen, L. (1999). "Uniform Connectedness and Classical Gestalt Principles of Perceptual Grouping." *Perception and Psychophysics*, 61, 661-674.

He BJ, Snyder AZ, Vincent JL, Epstein A, Shulman GL, Corbetta M. (2007). "Breakdown of Functional Connectivity in Front Parietal Networks Underlies Behavioral Deficits in Spatial Neglect." *Neuron*; 53(6): 905–18.

Heinrich, B. (1979). "Majoring" and "Minoring" by Foraging Bumblebees, *Bombus Vagans*: An Experimental Analysis." *Ecology*, 60, 245-255.

Hertwig, R. & Pleskac, T. J. (2008). "The Game of Life: How Small Samples Render Choice Simpler". In N. Chater & M. Oaksford (Eds.), *The Probabilistic Mind: Prospects for Bayesian Cognitive Science* (pp. 209-235). Oxford, England: Oxford University Press.

Hertwig, R., & Todd, P. M. (2003). "More is not Always Better: The Benefits of Cognitive Limits". In: Hardman, D., & Macchi, L. (Eds.) *Thinking: Psychological Perspectives on Reasoning, Judgment and Decision Making*. John Wiley and Sons, Ltd.

Hoffman, J. E., & Nelson, B. (1981). "Spatial Selectivity in Visual Search." *Perception & Psychophysics*, 30, 283–290.

Hopfinger JB, West VM. (2006) "Interactions Between Endogenous and Exogenous Attention on Cortical Visual Processing." *NeuroImage*; 31(2):774–89.

Humphreys, G. W., & Riddoch, M. J. (2003). "From What to Where: Neuropsychological Evidence for Implicit Interactions Between Object- and Space-Based Attention." *Psychological Science*, 14, 487–492.

Iani, C., Nicoletti, R., Rubichi, S., & Umiltà, C. (2001). "Shifting Attention Between Objects." *Cognitive Brain Research*, 11, 157–164.

Itti L. and Ch. Koch. (2001) "Computational Modeling of Visual Attention." *Nature Reviews Neuroscience*, Vol. 2, No. 3, pp. 194-203.

James, W. (1890). The principles of psychology. New York: Holt.

Jonides, J. (1981). "Voluntary vs. Automatic Control Over the Mind's Eye's Movement." In J. Long & A. Baddeley (Eds.), *Attention and performance IX* (pp. 187–203). Hillsdale: Erlbaum.

Kahneman, D., & Henik, A. (1981). "Perceptual Organization and Attention." In M. Kubovy & J. R. Pomerantz (Eds.), *Perceptual organization* (pp. 181–211). Hillsdale, NJ: Erlbaum.

Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). "The Reviewing of Object Files: Object-Specific Integration of Information." *Cognitive Psychology*, 24, 175–219. Doi: 10.1016/0010-0285(92)90007-O.

Kareev, Y. (1995). "Through a Narrow Window: Working Memory Capacity and the Detection of Covariation." *Cognition*, 56, 263–269.

Kareev, Y. (2000). "Seven (indeed, plus minus two) and the Detection of Correlations." *Psychological Review*, 107, 397–402.

Kareev, Y., Lieberman, I., & Lev, M. (1997). "Through a Narrow Window: Sample Size and the Perception of Correlation." *Journal of Experimental Psychology: General*, 126, 278–287.

Kareev, Y., & Fiedler, K. (2006). "Nonproportional Sampling and the Amplification of Correlations." *Psychological Science*, 17, 715-720.

Kareev, Y., & Fiedler, K. (2011). "Judge for Yourself: Reply to Evans and Buehner (2011)." *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 37, 1595-1598.

Kasai, T., Moriya, H., & Hirano, S. (2011). "Are Objects the Same as Groups? ERP Correlates of Spatial Attentional Guidance by Irrelevant Feature Similarity." *Brain Research*, 1399, 49–58.

Khayat PS, Spekreijse H, Roelfsema PR (2006) "Attention Lights Up new Object Representations Before the Old Ones Fade Away." *Journal of Neuroscience* 26:138–142.

Kellman, P. J. (2000). "An Update on Gestalt Psychology. In B. Landau & J. Sabini Eds.), *Perception, Cognition, and Language: Essays in honor of Henry and Lila Gleitman* pp. 157-190)". Cambridge, MA: MIT Press.

Kennerley, Steven W., Walton, Mark E., Behrens, Timothy E. J., Buckley, Mark J., Rushworth, Matthew F. S. (July 2006). "Optimal Decision Making and the Anterior Cingulate Cortex". *Nature Neuroscience*. 9 (7): 940–947. doi:10.1038/nn1724

Kiani, Roozbeh; Shadlen, Michael N. (2009). "Representation of Confidence Associated with a Decision by Neurons in the Parietal Cortex." *Science*. 324 (5928): 759–764. doi:10.1126/science.1169405.

Kim, Y.H., Gitelman, D.R., Nobre, A.C., Parrish, T.B., LaBar, K.S., Mesulam, M.M. (1999) "The Large-Scale Neural Network for Spatial Attention Displays Multi Functional Over Lap but Differential Asymmetry." *NeuroImage*; 9(3):269–77.

Kincade, J.M., Abrams, R.A., Astafiev, S.V., Shulman, G.L., Corbetta, M. (2005) "An Event-Related Functional Magnetic Resonance Imaging Study of Voluntary and Stimulus-Driven Orienting of Attention." *Journal of Neuroscience*; 25 (18): 4593–604.

Klein, R.M., Shore, D.I. (2000). "Relations Among Modes of Visual Orienting." In: Monsell S, Driver J, editors. *Attention & performance XVIII: control of cognitive processes*. Cambridge, MA: MIT Press; p.195–208.

Klein, R.M. (2004) "On the Control of Visual Orienting." In: Posner MI, editor. *Cognitive neuroscience of attention*. New York: Guilford Press. p. 29–44.

Klein, R.M. (2009) "On the Control of Attention." *Canadian Journal of Experimental Psychology*; 63(3):240–52.

Koch Ch. and S. Ullman. (1985). "Shifts in Selective Visual Attention: Towards the Underlying Neural Circuitry." *Human Neurobiology*, Vol. 4, pp. 219-227.

Koffka, K. (1922). "Principles of Gestalt Psychology." New York: Harcourt, Brace & World, Inc.

Krauss, S., & Wang, X. T. (2003). "The Psychology of the Monty Hall Problem: Discovering Psychological Mechanisms for Solving a Tenacious Brainteaser." *Journal of Experimental Psychology: General*, 132, 3–22.

Lamy, D., & Egeth, H. (2002). "Object-Based Selection: The Role of Attentional Shifts." *Perception & Psychophysics*, 64, 52–66. doi:10.3758/BF03194557

Lamy, D., & Tsal, Y. (2000). "Object Features, Object Locations, and Object Files: Which Does Selective Attention Activate and When?" *Journal of Experimental Psychology: Human Perception and Performance*, 26, 1387–1400. doi:10.1037/0096-1523.26.4.1387

Levine M.D. (1985). Vision in Man and Machine. McGraw-Hill.

Li, X., & Logan, G. D. (2008). "Object-Based Attention in Chinese Readers of Chinese Words: Beyond Gestalt Principles." *Psychonomic Bulletin & Review*, 15, 945–949.

Lupiáñez J, Decaix C, Siéoff E, Chokron S, Milliken B, Bartolomeo P. (2004). "Independent Effects of Endogenous and Exogenous Spatial Cueing: Inhibition of Return at Endogenously Attended Target Locations." *Experimental Brain Research* 2; 159(4): 447–57.

Marino, A. C., & Scholl, B. J. (2005). "The Role of Closure in Defining the "Objects" of Object-Based Attention." *Perception & Psychophysics*, 67, 1140–1149.

Marr, D. (1982). "Vision: A Computational Investigation Into the Human Representation and Processing of Visual Information." San Francisco, CA: Freeman.

Marrara, M. T., & Moore, C. M. (2003). "Object-Based Selection in the Two-Rectangles Method is not an Artifact of the Three-Sided Directional Cue." *Perception & Psychophysics*, 65, 1103-1109.

Martignon, L., & Hoffrage, U. (1999). "Why Does One-Reason Decision Making Work? A Case Study in Ecological Rationality." In G. Gigerenzer, P. M. Todd, & the ABC Group (Eds.), *Simple heuristics that make us smart* (pp. 119–140). Oxford, England: Oxford University Press.

Mayer AR, Dorflinger JM, Rao SM, Seidenberg M (2004). "Neural Networks Underlying Endogenous and Exogenous Visual-Spatial Orienting." *Neuroimage*; 23(2):534–41.

McCrae, C. S., & Abrams, R. A. (2001). "Age-Related Differences in Object- and Location-Based Inhibition of Return of Attention." *Psychology and Aging*, 16, 437–449. Doi: 10.1037/0882-7974.16.3.437.

McNamara, J. M., & Houston, A. I. (1985). "Optimal Foraging and Learning." *Journal of Theoretical Biology*, 117, 231-249.

McNamara, J. M., & Houston, A. I. (1987). "Memory and the Efficient Use of Information." *Journal of Theoretical Biology*, 125, 385-395.

Milanese R. (1993). "Detecting Salient Regions in an Image: from Biological Evidence to Computer implementation." PhD thesis, Dept. of Computer Science, University of Geneva, Switzerland.

Moore, C. M., Yantis, S., & Vaughan, B. (1998). "Object-Based Visual Selection: Evidence from Perceptual Completion." *Psychological Science*, 9, 104–110.
doi:10.1111/1467-9280.00019

Muller, H. J., & Humphreys, G. W. (1991). "Luminance-Increment Detection: Capacity Limited or Not?" *Journal of Experimental Psychology: Human Perception and Performance*, 17, 107–124.

Müller, H. J., & Krummenacher J. (2006). "Visual Search and Selective Attention." *Visual Cognition*, 2006, 14 (4/5/6/7/8), 389–410.

Müller, H. J., & Rabbitt, P. M. (1989). "Reflexive and Voluntary Orienting of Visual Attention: Time Course of Activation and Resistance to Interruption." *Journal of Experimental Psychology: Human Perception and Performance*, 15, 315–330.
doi:10.1037/0096-1523.15.2.315

Müller, H. J., & von Mühlenen, A. (1996). "Attentional Tracking and Inhibition of Return in Dynamic Displays." *Perception & Psychophysics*, 58, 224–249.

Nakayama, K., & Mackeben, M. (1989). "Sustained and Transient Components of Focal Visual Attention." *Vision Research*, 11, 1631–1647.

Newport, E.L. (1990). "Maturational Constraints on Language Learning." *Cognitive Science*, 14, 11–28.

Newport, E. L. (1988). "Constraints on Learning and Their Role in Language Acquisition: Studies of the Acquisition of American Sign Language." *Language Science*, 10, 147–172.

Niebur E. and Ch. Koch (1996). "Control of Selective Visual Attention: Modeling the Where Pathway." *Advances in Neural Information Processing Systems*, Vol. 8, pp. 802-808.

Niebur E. and Ch. Koch (1998). "Computational Architectures for Attention. The Attentive Brain." R Parasuraman, R., ed.,. MIT Press, Cambridge, Massachusetts, pp. 163-186.

Nobre AC, Sebestyen GN, Gitelman DR, Mesulam MM, Frackowiak RS, Frith CD (1997). "Functional Localization of the System for Visuospatial Attention Using Positron Emission Tomography." *Brain*; 120(Pt 3):515–33.

Öğmen, H., Patel, S. S., Bedell, H. E., & Camuz, K. (2004). "Differential Latencies and the Dynamics of the Position Computation Process for Attention Perception Psychophysics Moving Targets, Assessed with the Flash-Lag Effect." *Vision Research*, 44, 2109–2128.

Palmer, S. E. (1999a) Vision science: Photons to Phenomenology. Cambridge, MA: Bradford Books/MIT Press.

Pashler, H. (1998). The Psychology of Attention. Cambridge, MA: MIT Press.

Peelen MV, Heslenfeld DJ, Theeuwes J. (2004). "Endogenous and Exogenous Attention Shifts are Mediated by the Same Large-Scale Neural Network." *Neuroimage*; 22(2):822–30.

Pinna, B. (2014). "What is a Perceptual Object? Beyond the Gestalt Theory of Perceptual Organization." In A. Geremek, M. W. Greenlee, & S.

Posner M.I. & Cohen, Y. (1984). "Components of Visual Orienting." *Attention and Performance X* 32:531-556.

Posner M.I., Rafal RD, Choate LS, Vaughan J. (1985). "Inhibition of Return: Neural Basis and Function." *Cognitive Neuropsychology*; 2:211–28.

Posner, M.I. (1980). "Orienting of Attention." *Quarterly Journal of Experimental Psychology*, 32, 3–25. doi:10.1080/ 00335558008248231

Posner, M. I., Snyder, C. R. R., & Davidson, B. J. (1980). "Attention and the Detection of Signals." *Journal of Experimental Psychology. General*, 109, 106–174

Posner M.I. and S.E. Peterson (1990). "The Attention System in Human Brain." *Annual Review of Neuroscience*, Vol. 13, pp. 25-42.

Posner, M.I. and Fan, J. (2008) 'Attention as an Organ System', in Pomerantz, J.R. (ed.) *Topics in Integrative Neuroscience: From Cells to Cognition*. Cambridge: Cambridge University Press, pp. 31–61.

Prinzmetal, W. (1981). "Principles of Feature Integration in Visual Perception." *Perception and Psychophysics*, 30, 330-340.

Purushothaman, G., Patel, S. S., Bedell, H. E., & Ogmen, H. (1998). "Moving Ahead Through Differential Visual Latency." *Nature*, 396, 424.

Rakow, T., Demes, K. A., & Newell, B. R. (2008). "Biased Samples not Mode of Presentation: Reexamining the Apparent Underweighting of Rare Events in Experience-Based Choice." *Organizational Behavior and Human Decision Processes*, 106, 168-179.

Renner P, Klinger LG, Klinger MR (2006) “Exogenous and Endogenous Attention Orienting in Autism Spectrum Disorders.” *Child Neuropsychology* 12:361–382.

Reppa, I., Schmidt, W. C., & Leek, E. C. (2012). “Successes and Failures in Producing Attentional Object-based Cueing Effects.” *Attention, Perception, & Psychophysics*, 74, 43–69. doi:10.3758/s13414-011-0211-x

Ro, T., & Rafal, R. D. (1999). “Components of Reflexive Visual Orienting to Moving Objects.” *Perception & Psychophysics*, 61, 826–836.

Rosen, A.C., Rao, S.M., Caffarra, P., Scaglioni, A., Bobholz, J.A., Woodley, S.J., Hammeke, T.A., Cunningham, J.M., Prieto, T.E., Binder, J.R. (1999) “Neural Basis of Endogenous and Exogenous Spatial Orienting: A Functional MRI Study.” (*Magnetic resonance imaging*) *Journal of Cognitive Neuroscience* 11: 135-148

Sekuler R. and R. Blake. Perception. McGraw-Hill (2nd edition), 1990.

Scholl, B. J. (2001). “Objects and Attention: The State of the Art.” *Cognition*, 80, 1-46.

Scholl, B. J., & Leslie, A. M. (1999). “Explaining the Infant’s Object Concept: Beyond the Perception/Cognition Dichotomy.” In E. Lepore & Z. Pylyshyn (Eds.), *What is cognitive science?* (pp. 26–73). Oxford, UK: Blackwell.

Shafir, S., & Roughgarden, J. (1998). “Testing Predictions of Foraging Theory for a Sit-and-Wait Forager, *Anolis gingivinus*.” *Behavioral Ecology*, 9, 74-84.

Shulman, G. L., Remington, R. W., & McLean, J. P. (1979). "Moving Attention Through Visual Space." *Journal of Experimental Psychology: Human Perception and Performance*, 5, 522–526.

Snyder LH, Batista AP, Andersen RA (1997) "Coding of Intention in the Posterior Parietal Cortex." *Nature* 386:167–170. doi:10.1038/386167a0 pmid:9062187

Soto, D., & Blanco, M. J. (2004). "Spatial Attention and Object-based Attention: A Comparison Within a Single Task." *Vision Research*, 44, 69–81.

Theeuwes, J., Mathôt, S., & Grainger, J. (2013). "Exogenous Object-Centered Attention." *Attention, Perception, & Psychophysics*, 75, 812–818. doi:10.3758/s13414-013-0459-4.

Tipper, S. P., Driver, J., & Weaver, B. (1991). "Object-Centered Inhibition of Return of Visual Attention." *Quarterly Journal of Experimental Psychology*, 43A, 289–298. Doi: 10.1080/14640749108400971

Tipper, S.P., & Weaver, B. (1998). "The Medium of Attention: Location Based, Object Centered, or Scene Based." *Visual Attention* (pp. 77–107). New York: Oxford University Press.

Tipper, S. P., Jordan, H., & Weaver, B. (1999). "Scene-Based and Object-Centered Inhibition of Return: Evidence for Dual Orienting Mechanisms." *Perception & Psychophysics*, 61, 50–60.

Tipper, S. P., Weaver, B., Jerreat, L. M., & Burak, A. L. (1994). "Object- Based and Environment-Based Inhibition of Return of Visual Attention." *Journal of Experimental Psychology: Human Perception and Performance*, 20, 478–499. Doi: 10.1037/0096-1523.20.3.478.

Todd, J.J., Fougne D, Marois R. (2005). "Visual Short-Term Memory Load Suppresses Temporo-Parietal Junction Activity and Induces Inattentional Blindness." *Psychological Science*; 16(12):965–2.

Treisman, A. (1960). "Contextual Cues in Selective Listening." *Quarterly Journal of Experimental Psychology*, 12, 242–248.

Treisman, A. (1988). "Features and Objects: The Fourteenth Bartlett Memorial Lecture." *The Quarterly Journal of Experimental Psychology*, 40A(2), 201–237.

Treisman, A., & Gelade, G. (1980). "A Feature-Integration Theory of Attention." *Cognitive Psychology*, 12, 97–136.

Tsal, Y. (1983). "Movement of Attention Across the Visual Field." *Journal of Experimental Psychology: Human Perception & Performance*, 9, 523–530.

Umiltà, C., Castiello, U., Fontana, M., & Vestri, A. (1995). "Object-Centred Orienting of Attention." *Visual Cognition*, 2, 165–181. Doi: 10.1080/13506289508401729

Vecera, S. P., & Farah, M. J. (1994). "Does Visual Attention Select Objects or Locations?" *Journal of Experimental Psychology: General*, 123, 146-160.

Vecera, S. P. (1994). "Grouped Locations and Object-Based Attention: Comment on Egly, Driver, & Rafal (1994)." *Journal of Experimental Psychology: General*, 123, 316–320. doi:10.1037/0096-3445.123.3.316

Vickers, D., Smith, P., Burt, J., & Brown, M. (1985). "Experimental Paradigms Emphasizing State or Process Limitations: II. Effects on Confidence." *Acta Psychologica*, 59, 163–193.

Vivas, A. B., Humphreys, G. W., & Fuentes, L. J. (2008). "Object-Based Inhibition of Return in Patients with Posterior Parietal Damage." *Neuropsychology*, 22, 169–176.

Wagemans, J., Elder, J. H., Kubovy, M., Palmer, S. E., Peterson, M. A., Singh, M., & von der Heydt, R. (2012). "A Century of Gestalt Psychology in Visual Perception: I. Perceptual Grouping and Figure–Ground Organization." *Psychological Bulletin*, 138, 1172–1217.

Walton, Mark E.; Devlin, Joseph T.; Rushworth, Matthew F. S. (2004). "Interactions Between Decision Making and Performance Monitoring Within Prefrontal Cortex." *Nature Neuroscience*. 7 (11): 1259–1265. doi:10.1038/nn1339.

Warner CB, Juola JF, Koshino H. (1990) "Voluntary Allocation Versus Automatic Capture of Visual Attention." *Perception and Psychophysics*; 48:243–251.

Watson, S. E., & Kramer, A. F. (1999). "Object-Based Visual Selective Attention and Perceptual Organization." *Perception & Psychophysics*, 61, 31–49.

Weichselgartner, E., & Sperling, G. (1987). "Dynamics of Automatic and Controlled Visual Attention." *Science*, 238, 778–780. doi:10.1126/ science.3672124

Weaver, B., Lupiáñez, J., & Watson, F. L. (1998). "The Effects of Practice on Object-Based, Location-Based, and Static-Display Inhibition of Return." *Perception & Psychophysics*, 60, 993– 1003. Doi: 10.3758/BF03211934

Weiten, W. (1995). Psychology: Themes and Variations 3rd ed. New York: Brooks/Cole Publishing Company.

Wertheimer, M. (1923). "Laws of Organization in Perceptual Forms." In: W.A. Ellis (Ed.), *Sourcebook of Gestalt Psychology* (pp. 71–88). London: Routledge & Kegan Paul.

Wertheimer, M. (1950). "Laws of Organization in Perceptual Forms." In W. D. Ellis Ed., *A Source Book of Gestalt Psychology*. New York: Humanities Press. Original work published 1923).

Wilson, T. D., & Schooler, J. W. (1991). "Thinking Too Much: Introspection Can Reduce the Quality of Preferences and Decisions." *Journal of Personality and Social Psychology*, 60, 181–192.

Yantis, S., & Jonides, J. (1996). "Attentional Capture by Abrupt Onsets: New Perceptual Objects or Visual Masking." *Journal of Experimental Psychology. Human Perception and Performance*, 22, 1505–1513.

Yantis S. (1998) "Control of Visual Attention." In: Pashler H, editor. *Attention*. London: Psychology Press;. p. 223–56.

Yantis S. (2000) “Goal Directed and Stimulus Driven Determinants of Attentional Control.” In: Monsell S, Driver J, editors. *Control of cognitive processes: attention and performance XVIII*. Cambridge, MA: MIT Press. p. 73–103.

Yantis S, Jonides J. (1990) “Abrupt Visual Onsets and Selective Attention: Voluntary Versus Automatic Allocation.” *Journal of Experimental Psychology: Human Perception and Performance*; 16(1): 121–34.

Yuan, J., & Fu, S. (2014). “Attention Can Operate on Semantic Objects Defined by Individual Chinese Characters.” *Visual Cognition*, 22, 770–788.

Zhao, L., Cosman, J. D., Vatterott, D. B., Gupta, P., & Vecera, S. P. (2014). “Visual Statistical Learning Can Drive Object-Based Attentional Selection.” *Attention, Perception & Psychophysics*, 76, 2240.

Appendix-A

Appendix-A shows the simulation carried for a threshold value between 0.1 and 0.9. To obtain an estimate, we implemented an error formula, and we picked the threshold minimizing the error.

Table A.A-1. Simulation results for threshold values between 0.1 and 0.9 with a step size of 0.01.
The row with the yellow highlight shows t for which the error is minimum.

Threshold	Correct	No choice	Incorrect	Error	Error %
0.1	8069	999	1732	13807818	1278.501667
0.11	8018	1091	1691	12981542	1201.99463
0.12	7961	1196	1643	12070472	1117.636296
0.13	7926	1293	1581	11270546	1043.569074
0.14	7881	1380	1539	10567496	978.4718519
0.15	7833	1480	1487	9790152	906.4955556
0.16	7764	1601	1435	8881838	822.3924074
0.17	7711	1693	1396	8220446	761.1524074
0.18	7662	1794	1344	7529858	697.2090741
0.19	7614	1895	1291	6870566	636.1635185
0.2	7550	2005	1245	6179474	572.1735185
0.21	7490	2103	1207	5592798	517.8516667
0.22	7451	2180	1169	5157176	477.5162963
0.23	7404	2275	1121	4644906	430.0838889
0.24	7355	2372	1073	4149176	384.182963
0.25	7305	2476	1019	3650568	338.0155556
0.26	7269	2567	964	3245834	300.5401852
0.27	7229	2653	918	2882474	266.8957407
0.28	7171	2756	873	2469912	228.6955556
0.29	7127	2851	822	2123750	196.6435185
0.3	7071	2952	777	1779512	164.7696296
0.31	7024	3044	732	1495158	138.4405556
0.32	6968	3150	682	1197882	110.915
0.33	6921	3250	629	951936	88.14222222
0.34	6866	3353	581	725906	67.21351852
0.35	6816	3457	527	533382	49.38722222
0.36	6711	3591	498	310982	28.79462963
0.37	6613	3713	474	159594	14.77722222
0.38	6496	3854	450	46554	4.310555556

0.39	6373	4012	415	536	0.04962963
0.4	6270	4149	381	26834	2.48462963
0.41	6135	4302	363	135896	12.58296296
0.42	6014	4447	339	312374	28.92351852
0.43	5875	4605	320	593174	54.92351852
0.44	5756	4752	292	923742	85.53166667
0.45	5643	4883	274	1288334	119.2901852
0.46	5537	5009	254	1692338	156.697963
0.47	5456	5122	222	2080082	192.6001852
0.48	5369	5219	212	2473538	229.0312963
0.49	5313	5296	191	2787432	258.0955556
0.5	5226	5408	166	3288086	304.4524074
0.51	5190	5456	154	3512918	325.2701852
0.52	5156	5507	137	3751802	347.3890741
0.53	5128	5549	123	3954606	366.1672222
0.54	5089	5601	110	4221938	390.9201852
0.55	5048	5653	99	4502174	416.867963
0.56	4989	5717	94	4877834	451.6512963
0.57	4932	5776	92	5243550	485.5138889
0.58	4863	5847	90	5702486	528.007963
0.59	4801	5912	87	6136872	568.2288889
0.6	4742	5974	84	6565898	607.9535185
0.61	4689	6031	80	6969858	645.3572222
0.62	4639	6087	74	7372694	682.6568519
0.63	4594	6136	70	7738118	716.4924074
0.64	4558	6177	65	8045786	744.9801852
0.65	4517	6220	63	8384792	776.3696296
0.66	4417	6324	59	9236648	855.2451852
0.67	4326	6417	57	10039082	929.5446296
0.68	4227	6519	54	10955198	1014.370185
0.69	4145	6606	49	11759328	1088.826667
0.7	4045	6709	46	12759914	1181.473519
0.71	3898	6857	45	14283906	1322.583889
0.72	3744	7013	43	15980174	1479.645741
0.73	3593	7169	38	17757986	1644.257963
0.74	3440	7325	35	19640414	1818.556852
0.75	3308	7458	34	21329154	1974.921667
0.76	3223	7544	33	22456536	2079.308889
0.77	3148	7622	30	23492346	2175.217222
0.78	3076	7696	28	24501662	2268.672407
0.79	3015	7757	28	25359566	2348.107963
0.8	2930	7845	25	26604954	2463.421667
0.81	2772	8007	21	28985762	2683.866852

0.82	2630	8149	21	31180514	2887.08463
0.83	2506	8277	17	33200042	3074.077963
0.84	2355	8430	15	35717624	3307.187407
0.85	2221	8566	13	38031392	3521.425185
0.86	2073	8717	10	40679666	3766.635741
0.87	1936	8854	10	43181834	3998.317963
0.88	1772	9018	10	46275858	4284.801667
0.89	1604	9186	10	49556898	4588.601667
0.9	1462	9329	9	52429578	4854.590556

Appendix-B

Appendix-B shows the second simulation to “fine-tune” the threshold used by the subjects. The step size was decreased from 0.01 to 0.001. The threshold range was from 0.3 to 0.5. The error value decreased from 536 to 494 with a threshold value of 0.391 corresponding to 6360 correct, 4029 no choice and 411 incorrect trials.

Table A.B-1. Simulation results for threshold values between 0.3 and 0.5 with a step size of 0.001. The row with the yellow highlight shows *t* for which the error is minimum.

Threshold	Correct	No choice	Incorrect	Error	Error %
0.3	7071	2952	777	1779512	164.7696296
0.301	7067	2959	774	1756718	162.6590741
0.302	7064	2964	772	1740438	161.1516667
0.303	7059	2973	768	1711574	158.4790741
0.304	7055	2979	766	1692054	156.6716667
0.305	7047	2990	763	1656152	153.3474074
0.306	7039	3003	758	1615094	149.5457407
0.307	7035	3013	752	1585158	146.7738889
0.308	7034	3018	748	1570914	145.455
0.309	7032	3029	739	1539998	142.5924074
0.31	7024	3044	732	1495158	138.4405556
0.311	7019	3055	726	1463246	135.4857407
0.312	7013	3066	721	1431072	132.5066667
0.313	7011	3075	714	1406846	130.2635185
0.314	7003	3087	710	1371566	126.9968519
0.315	6999	3094	707	1351608	125.1488889
0.316	6994	3103	703	1326254	122.8012963
0.317	6991	3109	700	1309694	121.267963
0.318	6984	3124	692	1269078	117.5072222
0.319	6976	3138	686	1230866	113.9690741
0.32	6968	3150	682	1197882	110.915
0.321	6963	3159	678	1174046	108.707963
0.322	6958	3168	674	1150454	106.5235185
0.323	6954	3181	665	1118778	103.5905556
0.324	6951	3191	658	1094822	101.3724074
0.325	6949	3197	654	1080474	100.0438889
0.326	6946	3207	647	1057022	97.87240741

0.327	6940	3217	643	1031966	95.55240741
0.328	6934	3228	638	1005134	93.06796296
0.329	6930	3236	634	986078	91.30351852
0.33	6921	3250	629	951936	88.14222222
0.331	6911	3268	621	909896	84.24962963
0.332	6907	3277	616	889862	82.39462963
0.333	6901	3287	612	866922	80.27055556
0.334	6896	3294	610	850554	78.755
0.335	6891	3306	603	825032	76.39185185
0.336	6887	3316	597	804200	74.46296296
0.337	6885	3320	595	795704	73.6762963
0.338	6879	3331	590	772278	71.50722222
0.339	6873	3342	585	749216	69.37185185
0.34	6866	3353	581	725906	67.21351852
0.341	6860	3365	575	701894	64.99018519
0.342	6856	3376	568	681182	63.07240741
0.343	6854	3387	559	662094	61.305
0.344	6848	3399	553	639306	59.195
0.345	6840	3410	550	617234	57.1512963
0.346	6838	3415	547	608342	56.32796296
0.347	6833	3426	541	588672	54.50666667
0.348	6826	3439	535	565214	52.33462963
0.349	6821	3447	532	550602	50.98166667
0.35	6816	3457	527	533382	49.38722222
0.351	6809	3468	523	513864	47.58
0.352	6801	3477	522	496802	46.00018519
0.353	6789	3494	517	467168	43.2562963
0.354	6776	3512	512	436622	40.42796296
0.355	6763	3526	511	411992	38.14740741
0.356	6748	3544	508	382286	35.39685185
0.357	6739	3554	507	365928	33.88222222
0.358	6727	3571	502	340550	31.53240741
0.359	6717	3582	501	323552	29.95851852
0.36	6711	3591	498	310982	28.79462963
0.361	6696	3608	496	286286	26.50796296
0.362	6687	3621	492	269150	24.9212963
0.363	6675	3634	491	251304	23.26888889
0.364	6662	3647	491	233702	21.63907407
0.365	6651	3660	489	217496	20.13851852
0.366	6642	3673	485	202578	18.75722222
0.367	6635	3683	482	191438	17.72574074
0.368	6626	3695	479	178286	16.50796296
0.369	6620	3703	477	169778	15.72018519

0.37	6613	3713	474	159594	14.77722222
0.371	6598	3729	473	142826	13.22462963
0.372	6584	3745	471	127286	11.78574074
0.373	6576	3757	467	116862	10.82055556
0.374	6556	3777	467	98942	9.161296296
0.375	6547	3788	465	90168	8.348888889
0.376	6539	3801	460	80838	7.485
0.377	6529	3814	457	71648	6.634074074
0.378	6518	3827	455	62846	5.819074074
0.379	6504	3842	454	53234	4.929074074
0.38	6496	3854	450	46554	4.310555556
0.381	6487	3866	447	40200	3.722222222
0.382	6471	3885	444	30926	2.863518519
0.383	6449	3911	440	20258	1.875740741
0.384	6435	3928	437	14568	1.348888889
0.385	6424	3942	434	10634	0.98462963
0.386	6411	3961	428	6342	0.587222222
0.387	6401	3972	427	4392	0.406666667
0.388	6392	3986	422	2450	0.226851852
0.389	6383	3997	420	1406	0.130185185
0.39	6373	4012	415	536	0.04962963
0.391	6360	4029	411	494	0.045740741
0.392	6352	4042	406	962	0.089074074
0.393	6341	4054	405	2144	0.198518519
0.394	6334	4064	402	3318	0.307222222
0.395	6327	4074	399	4808	0.445185185
0.396	6307	4097	396	9942	0.920555556
0.397	6296	4113	391	14166	1.311666667
0.398	6288	4127	385	18266	1.691296296
0.399	6280	4137	383	21926	2.030185185
0.4	6270	4149	381	26834	2.48462963
0.401	6256	4166	378	34602	3.203888889
0.402	6239	4185	376	44766	4.145
0.403	6226	4199	375	53214	4.927222222
0.404	6208	4219	373	66386	6.146851852
0.405	6195	4234	371	77064	7.135555556
0.406	6184	4246	370	86378	7.997962963
0.407	6171	4261	368	98502	9.120555556
0.408	6157	4277	366	112362	10.40388889
0.409	6146	4288	366	122966	11.38574074
0.41	6135	4302	363	135896	12.58296296
0.411	6126	4315	359	147966	13.70055556
0.412	6113	4333	354	165794	15.3512963

0.413	6107	4339	354	172718	15.99240741
0.414	6097	4351	352	186050	17.22685185
0.415	6081	4369	350	207474	19.21055556
0.416	6067	4388	345	229848	21.28222222
0.417	6053	4404	343	250776	23.22
0.418	6043	4416	341	266792	24.70296296
0.419	6024	4437	339	296894	27.49018519
0.42	6014	4447	339	312374	28.92351852
0.421	5999	4463	338	337334	31.23462963
0.422	5986	4479	335	361934	33.51240741
0.423	5972	4494	334	387018	35.835
0.424	5962	4510	328	411242	38.07796296
0.425	5947	4525	328	438662	40.61685185
0.426	5940	4533	327	452918	41.93685185
0.427	5924	4550	326	484826	44.8912963
0.428	5910	4567	323	516246	47.80055556
0.429	5888	4591	321	564122	52.23351852
0.43	5875	4605	320	593174	54.92351852
0.431	5861	4620	319	625176	57.88666667
0.432	5852	4631	317	648050	60.00462963
0.433	5838	4649	313	685706	63.4912963
0.434	5823	4666	311	723912	67.02888889
0.435	5812	4677	311	750422	69.48351852
0.436	5798	4695	307	790902	73.23166667
0.437	5783	4714	303	835016	77.3162963
0.438	5775	4727	298	863606	79.96351852
0.439	5765	4739	296	893114	82.69574074
0.44	5756	4752	292	923742	85.53166667
0.441	5744	4766	290	959738	88.86462963
0.442	5729	4782	289	1003104	92.88
0.443	5718	4796	286	1039502	96.25018519
0.444	5709	4808	283	1070744	99.14296296
0.445	5696	4822	282	1110602	102.8335185
0.446	5688	4831	281	1136202	105.2038889
0.447	5679	4841	280	1165118	107.8812963
0.448	5660	4860	280	1223334	113.2716667
0.449	5649	4874	277	1263488	116.9896296
0.45	5643	4883	274	1288334	119.2901852
0.451	5631	4896	273	1328792	123.0362963
0.452	5625	4905	270	1354274	125.3957407
0.453	5615	4916	269	1389128	128.622963
0.454	5606	4930	264	1429346	132.3468519
0.455	5590	4949	261	1489794	137.9438889

0.456	5578	4961	261	1531122	141.7705556
0.457	5568	4971	261	1566002	145.0001852
0.458	5562	4980	258	1593662	147.5612963
0.459	5552	4993	255	1635878	151.4701852
0.46	5537	5009	254	1692338	156.697963
0.461	5529	5022	249	1733024	160.4651852
0.462	5522	5032	246	1765862	163.5057407
0.463	5507	5050	243	1829192	169.3696296
0.464	5499	5058	243	1859624	172.1874074
0.465	5492	5067	241	1891242	175.115
0.466	5486	5075	239	1919246	177.707963
0.467	5480	5084	236	1949894	180.5457407
0.468	5471	5095	234	1990166	184.2746296
0.469	5467	5104	229	2018408	186.8896296
0.47	5456	5122	222	2080082	192.6001852
0.471	5441	5137	222	2141042	198.2446296
0.472	5430	5150	220	2191514	202.917963
0.473	5421	5160	219	2231576	206.6274074
0.474	5415	5166	219	2256728	208.9562963
0.475	5409	5172	219	2282024	211.2985185
0.476	5402	5180	218	2314382	214.2946296
0.477	5393	5190	217	2355552	218.1066667
0.478	5387	5197	216	2384102	220.7501852
0.479	5380	5207	213	2422626	224.3172222
0.48	5369	5219	212	2473538	229.0312963
0.481	5364	5228	208	2506694	232.1012963
0.482	5360	5234	206	2530034	234.2624074
0.483	5355	5243	202	2563598	237.3701852
0.484	5350	5248	202	2586038	239.447963
0.485	5344	5256	200	2618798	242.4812963
0.486	5337	5264	199	2653448	245.6896296
0.487	5333	5273	194	2686154	248.717963
0.488	5325	5282	193	2725856	252.3940741
0.489	5317	5291	192	2765850	256.0972222
0.49	5313	5296	191	2787432	258.0955556
0.491	5304	5307	189	2835554	262.5512963
0.492	5298	5316	186	2872862	266.0057407
0.493	5293	5325	182	2908682	269.3224074
0.494	5282	5337	181	2964402	274.4816667
0.495	5272	5350	178	3021962	279.8112963
0.496	5261	5362	177	3078752	285.0696296
0.497	5252	5374	174	3132458	290.0424074
0.498	5242	5387	171	3191622	295.5205556

0.499	5228	5404	168	3271526	302.9190741
0.5	5226	5408	166	3288086	304.4524074

