

# **Temporal Limits of Multiple Object Tracking and Resource Theory**



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WEI-YING CHEN

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## Contributions of the Candidate

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The research presented in this thesis represents work undertaken by the Candidate in the School of Psychology at the University of Sydney. Ethic approval was granted by the University of Sydney Human Research Ethics Committee.

The candidate was responsible for coordinating the research, under the guidance and supervision of Associate Professor Alex O. Holcombe. The Candidate took primary responsibility for all aspects of the research including topic identification, study design, formulation of hypotheses, data collection, statistical analysis and interpretation of results. The candidate wrote and was the principle author of all manuscripts presented in this thesis, under the assistance and supervision of primary supervisor. Most of experiments in this thesis have been made in three articles and published in *Cognition*, *Journal of Vision*, and *Attention, Perception, & Psychophysics*. One of them was collaboratively published with Dr. Piers D. Howe at the University of Melbourne.

## Statement of Authentication

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This thesis is submitted to the University of Sydney in fulfilment of the requirement for Doctor of Philosophy.

The work presented in this thesis is, to the best of my knowledge and belief, original except as acknowledged in the text. I hereby declare that I have not submitted this material, either in full or in part, for a degree at this or any other institution.

Signature.....

Date.....

## **Abstract**

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The attentional capacity limitation of tracking multiple moving objects has been discussed expansively by various theoreticians. The research reported in this thesis assessed the limits of object tracking with a series of systematic psychophysical investigations. Chapter 2 reports evidence that the limits of object tracking are directly due to the resources allocated to each target rather than caused by spatial interference (Franconeri et al., 2008; 2010). With widely-spaced target configurations, the maximum speed observers could track targets declined as the number of targets increased. Chapter 4 provides evidence supporting the claim that tracking resources are flexibly shared among targets, with the fastest-moving target receiving more resources than the slower-moving target. These results provide concrete evidence to support the assumptions of resource theory: continuously allocated resources, limited capacity, and flexible resource allocation.

The current research also demonstrated some specific findings regarding resource theory in object tracking. Chapters 3 and 4 confirmed previous findings obtained using different methodologies (Alvarez & Cavanagh, 2005) by showing that tracking resources are largely hemisphere-specific, and effectively demonstrated that performance for a fast-moving target is very sensitive to the amount of resources allocated. Furthermore, Chapter 5 showed that observers lost the tracked target if distractors occupied a location close to the time a target occupied it, suggesting that the mechanism of tracking also has a limited temporal resolution, and that reducing the resource allocated to each target reduces temporal resolution. To conclude, the findings of all the experiments are discussed in the context of various resource theories.

## Table of Contents

---

|   |             |
|---|-------------|
| <b>ACKNOWLEDGMENTS .....</b>  | <b>I</b>    |
| <b>ABSTRACT .....</b>   | <b>V</b>    |
| <b>LIST OF FIGURES .....</b>  | <b>XI</b>   |
| <b>LIST OF TABLES .....</b>   | <b>XIII</b> |
| <b>CHAPTER 1 : GENERAL INTRODUCTION.....</b>  | <b>1</b>    |
| 1.1 UNDERSTANDING THE ATTENTIONAL PROCESS .....   | 2           |
| 1.2 RESOURCE THEORY .....   | 5           |
| 1.2.1 What is Resource Theory?.....   | 5           |
| 1.2.2 The History of Resource Theory.....   | 7           |
| 1.2.3 First Characteristic of Resource Theory: Continuously Allocated Resource.....                             | 8           |
| 1.2.4 The Second Characteristic of Resource Theory: Limited Capacity.....                                       | 10          |
| 1.2.5 Third Characteristic of Resource Theory: Flexible Allocation of Resource.....                             | 11          |
| 1.2.6 Summary of Resource Theory.....   | 14          |
| 1.3 MULTIPLE OBJECT TRACKING .....  | 15          |
| 1.3.1 Multiple Object Tracking (MOT) Paradigm .....   | 16          |
| 1.3.1.1 Spatial interference theory .....   | 17          |
| 1.3.1.2 FINST (slots theory).....   | 18          |
| 1.3.1.3 Serial switching theory.....  | 19          |
| 1.3.1.4 Flexible resource theory (FLEX theory) .....  | 19          |
| 1.3.2 Debate among the Four Theories.....   | 20          |
| 1.4 HEMISPHERE-SPECIFIC RESOURCE THEORY .....   | 22          |
| 1.5 FLEXIBLE RESOURCE ALLOCATION RELATED TO MULTIPLE OBJECT TRACKING.....                                       | 23          |
| 1.6 TEMPORAL RESOLUTION OF ATTENTION AND RESOURCE THEORY .....  | 26          |
| 1.7 QUESTIONS IN THIS THESIS .....  | 28          |
| <b>CHAPTER 2 : THE TRACKING RESOURCE THEORY AND THE REDUCTION IN SPEED<br/>LIMIT BY ADDITIONAL TARGETS.....</b> | <b>30</b>   |
| 2.1 INTRODUCTION OF CHAPTER 2 .....   | 30          |
| 2.1.1 Object Speed and Tracking Performance .....   | 31          |
| 2.1.2 The Proximity Confound .....  | 31          |
| 2.2 EXPERIMENT 1: TARGET NUMBER EFFECT ON SPEED LIMITS.....   | 34          |
| 2.2.1 Method.....   | 36          |
| 2.2.1.1 Participants .....  | 36          |
| 2.2.1.2 Stimuli .....   | 36          |
| 2.2.1.3 Procedure.....  | 37          |
| 2.2.1.4 Data Analysis .....   | 38          |

|   |           |
|---|-----------|
| 2.2.1.4.1 The resource-versus-performance function .....                                    | 39        |
| 2.2.1.4.2 The capacity-one benchmark .....  | 41        |
| 2.2.2 <i>Results</i> .....  | 43        |
| 2.2.3 <i>Discussion</i> .....   | 46        |
| 2.3 EXPERIMENT 2: CONSTANT TRAVELLED DISTANCE, BILATERAL ARRANGEMENT .....                  | 49        |
| 2.3.1 <i>Method</i> .....   | 50        |
| 2.3.1.1 Participants .....  | 50        |
| 2.3.1.2 Stimuli .....   | 50        |
| 2.3.1.3 Procedure .....   | 51        |
| 2.3.2 <i>Results</i> .....  | 52        |
| 2.3.3 <i>Discussion</i> .....   | 53        |
| 2.4 EXPERIMENT 3: EQUAL-DISTANCE EXPERIMENT WITH EYE TRACKER MONITORING .....               | 54        |
| 2.4.1 <i>Method</i> .....   | 55        |
| 2.4.1.1 Participants .....  | 55        |
| 2.4.1.2 Stimuli .....   | 55        |
| 2.4.1.3 Procedure .....   | 55        |
| 2.4.1.4 Eye Tracking .....  | 56        |
| 2.4.1.5 Data Analysis .....   | 56        |
| 2.4.2 <i>Results</i> .....  | 57        |
| 2.4.3 <i>Discussion</i> .....   | 58        |
| 2.5 DISCUSSION OF EXPERIMENTS 1-3 .....   | 59        |
| 2.5.1 <i>Spatial Interference is Not the Main Reason For Decrease of Speed Limits</i> ..... | 60        |
| 2.5.2 <i>Resource Costs Are Described by the Capacity-One Benchmark</i> .....               | 62        |
| 2.5.3 <i>Tracking Resource might be Hemisphere-Specific</i> .....                           | 64        |
| 2.6 CONCLUSION OF CHAPTER 2 .....   | 65        |
| <b>CHAPTER 3 : TRACKING RESOURCE IS HEMISPHERE-SPECIFIC .....</b>                           | <b>66</b> |
| 3.1 INTRODUCTION OF CHAPTER 3 .....   | 66        |
| 3.1.1 <i>Hemisphere Specificity</i> .....   | 66        |
| 3.1.2 <i>Capacity-one benchmark</i> .....   | 68        |
| 3.2 EXPERIMENT 4: TESTING HEMIFIELD SPECIFICITY OF THE TRACKING RESOURCE .....              | 70        |
| 3.2.1 <i>Method</i> .....   | 70        |
| 3.2.1.1 Participants .....  | 70        |
| 3.2.1.2 Stimuli .....   | 70        |
| 3.2.1.3 Procedure .....   | 71        |
| 3.2.1.4 Data Analysis .....   | 73        |
| 3.2.2 <i>Results and Discussion</i> .....   | 75        |
| 3.3 EXPERIMENT 5: HIGH LOADS (2 Vs. 4 TARGETS) WITH CONSTANT TRAVELLED DISTANCE. ....       | 79        |
| 3.3.1 <i>Method</i> .....   | 81        |
| 3.3.1.1 Participants .....  | 81        |



|   |            |
|---|------------|
| 3.3.1.2 Stimuli .....   | 81         |
| 3.3.1.3 Procedure.....  | 81         |
| 3.3.1.4 Data Analysis .....   | 82         |
| 3.3.2 <i>Results and Discussion</i> .....                                       | 83         |
| 3.4 EXPERIMENT 6: EYE TRACKING AND CONSTANT NUMBER OF REVERSALS.....            | 86         |
| 3.4.1 <i>Method</i> .....   | 87         |
| 3.4.1.1 Participants.....   | 87         |
| 3.4.1.2 Stimuli and Procedure .....   | 87         |
| 3.4.1.3 Eye Tracking .....  | 88         |
| 3.4.2 <i>Results and Discussion</i> .....                                       | 88         |
| 3.5 EXPERIMENT 7: VARYING TARGET-TARGET SEPARATIONS WITHIN A HEMIFIELD .....    | 91         |
| 3.5.1 <i>Method</i> .....   | 92         |
| 3.5.1.1 Participants.....   | 92         |
| 3.5.1.2 Stimuli .....   | 92         |
| 3.5.1.3 Procedure.....  | 92         |
| 3.5.2 <i>Results and Discussion</i> .....                                       | 94         |
| 3.6 DISCUSSION OF EXPERIMENTS 4-7 .....   | 98         |
| 3.6.1 <i>Hemisphere-Specific Resource Theory</i> .....                          | 98         |
| 3.6.2 <i>Excluding the Confound from Spatial Interference</i> .....             | 100        |
| 3.6.3 <i>Tracking Resource is not Completely Hemisphere-Specific</i> .....      | 101        |
| 3.7 CONCLUSION OF CHAPTER 3 .....   | 103        |
| <b>CHAPTER 4 : DIFFERENTIAL TRACKING RESOURCE ALLOCATION .....</b>              | <b>104</b> |
| 4.1 INTRODUCTION OF CHAPTER 4 .....   | 104        |
| 4.1.1 <i>Variable Resource Allocation</i> .....                                 | 105        |
| 4.1.2 <i>Tracking Resource Reallocation</i> .....                               | 107        |
| 4.2 EXPERIMENT 8: RESOURCE ALLOCATION BETWEEN TARGETS OF DIFFERENT SPEEDS ..... | 110        |
| 4.2.1 <i>Method</i> .....   | 111        |
| 4.2.1.1 Participants.....   | 111        |
| 4.2.1.2 Stimuli .....   | 111        |
| 4.2.1.3 Procedure.....  | 113        |
| 4.2.1.4 Data Analysis .....   | 113        |
| 4.2.2 <i>Results and Discussion</i> .....                                       | 114        |
| 4.3 EXPERIMENT 9: INEFFICIENT RESOURCE REALLOCATION BETWEEN TARGETS. ....       | 116        |
| 4.3.1 <i>Method</i> .....   | 119        |
| 4.3.1.1 Participants.....   | 119        |
| 4.3.1.2 Stimuli .....   | 119        |
| 4.3.1.3 Data Analysis .....   | 120        |
| 4.3.2 <i>Results and Discussion</i> .....                                       | 121        |
| 4.4 DISCUSSION OF EXPERIMENTS 8-9 .....   | 125        |

|   |            |
|---|------------|
| 4.4.1 Differential Allocation of the Hemisphere-Specific Resource .....               | 125        |
| 4.4.2 Serial Models and Unequal Time-Sharing within a Hemifield .....                 | 128        |
| 4.4.3 Parallel Models and Differential Resource Allocation.....                       | 129        |
| 4.4.4 Attention and the Tracking Resource .....                                       | 132        |
| 4.5 CONCLUSION OF CHAPTER 4 .....   | 133        |
| <b>CHAPTER 5 :TRACKING PERFORMANCE IS CONSTRAINED BY TEMPORAL<br/>RESOLUTION.....</b> | <b>134</b> |
| 5.1 INTRODUCTION OF CHAPTER 5 .....   | 134        |
| 5.1.1 Temporal Limits on Tracking.....  | 136        |
| 5.2 EXPERIMENT 10: TWO-RING EXPERIMENT .....  | 139        |
| 5.2.1 Method.....   | 139        |
| 5.2.1.1 Participants .....  | 139        |
| 5.2.1.2 Stimuli .....   | 140        |
| 5.2.1.3 Procedure.....  | 141        |
| 5.2.1.4 Data Analysis .....   | 142        |
| 5.2.2 Results and discussion.....   | 143        |
| 5.2.2.1 Effect of Target Number on Tracking Limits .....                              | 147        |
| 5.2.2.2 Concern of Spatial Interference.....  | 148        |
| 5.2.2.3 Effect of Eccentricity .....  | 150        |
| 5.2.2.4 Capacity-one benchmark.....   | 152        |
| 5.3 EXPERIMENT 11: THREE-RING EXPERIMENT .....  | 153        |
| 5.3.1 Method.....   | 154        |
| 5.3.1.1 Participants .....  | 154        |
| 5.3.1.2 Stimuli .....   | 154        |
| 5.3.1.3 Procedure.....  | 155        |
| 5.3.2 Results and discussion.....   | 156        |
| 5.3.2.1 Concern of Spatial Interference.....  | 159        |
| 5.3.2.2 Effect of eccentricity .....  | 160        |
| 5.4 DISCUSSION OF EXPERIMENTS 10-11.....  | 161        |
| 5.4.1 Parallel Theories of Tracking- Flexible Resource Theory.....                    | 162        |
| 5.4.2 Serial Switching Theories of Tracking .....                                     | 163        |
| 5.4.3 Difference between Temporal and Spatial Limits on Tracking.....                 | 165        |
| 5.5 CONCLUSION OF CHAPTER 5 .....   | 167        |
| <b>CHAPTER 6 :GENERAL DISCUSSION AND CONCLUSION.....</b>                              | <b>168</b> |
| 6.1 RESOURCE THEORY ACCOUNTS FOR THE PERFORMANCE OF MULTIPLE OBJECT TRACKING .        | 168        |
| 6.1.1 Excluding Cross-Talk Theory.....  | 168        |
| 6.1.2 Rejecting the Central Bottleneck Theory.....                                    | 172        |
| 6.1.3 Supporting Resource Theory.....   | 176        |

|  |            |
|--|------------|
| 6.2 TRACKING RESOURCE PER TARGET DETERMINES TEMPORAL RESOLUTION .....  | 183        |
| 6.3 HOW DOES THE TRACKING RESOURCE MEDIATE TRACKING PERFORMANCE?.....  | 188        |
| 6.4 THE NEURAL MECHANISMS OF THE RESOURCE ALLOCATION EFFECT ON SPEED LIMIT AND<br>TEMPORAL FREQUENCY LIMIT ..... | 189        |
| 6.5 RESOURCE THEORY IN MULTIPLE OBJECT TRACKING: AN ELECTROPHYSIOLOGY VIEW .....                                 | 192        |
| 6.6 CONCLUSION .....   | 195        |
| <b>REFERENCES.....</b>   | <b>196</b> |
| <b>PARTICIPANT CONSENT FORM .....</b>  | <b>205</b> |

## List of Figures

|  |     |
|--|-----|
| Figure 1.1 Cartoon representation of slot theory and resource theory.....            | 6   |
| Figure 1.2. Schematic description of resource theory .....                           | 8   |
| Figure 1.3. The resource-versus-performance function.....                            | 9   |
| Figure 2.1. A schematic of the trial sequence for all experiments in Chapter 2 ..... | 37  |
| Figure 2.2. Hypothetical tracking resource-versus-performance functions.....         | 39  |
| Figure 2.3. Individuals' performance in Experiment 1.....                            | 44  |
| Figure 2.4. Averaged speed limits in Experiment 1.....                               | 45  |
| Figure 2.5. Display of Experiment 2.....   | 51  |
| Figure 2.6. Results of Experiment 2 .....  | 52  |
| Figure 2.7. Display of Experiment 3.....   | 55  |
| Figure 2.8. Results of Experiment 3 .....  | 57  |
| Figure 2.9. Resource-versus-performance functions at high speeds.....                | 63  |
| Figure 3.1. Display of Experiment 4.....   | 72  |
| Figure 3.2. A schematic of the trial sequence for all experiments in Chapter 3.....  | 72  |
| Figure 3.3. Individuals' performance in Experiment 4.....                            | 76  |
| Figure 3.4. Averaged Speed Limits in Experiment 4.....                               | 79  |
| Figure 3.5. Schematic of the displays in Experiments 5 and 6.....                    | 82  |
| Figure 3.6. Results of Experiment 5 .....  | 84  |
| Figure 3.7. Results of Experiment 6 .....  | 89  |
| Figure 3.8. Display of Experiment 7.....   | 93  |
| Figure 3.9. Individuals' performance in Experiment 7.....                            | 94  |
| Figure 3.10. Averaged Speed Limits in Experiment 7.....                              | 95  |
| Figure 4.1. Display of Experiment 8.....   | 112 |
| Figure 4.2. Results of Experiment 8 .....  | 115 |
| Figure 4.3. Display of Experiment 9.....   | 121 |
| Figure 4.4. Individuals' performance in Experiment 9.....                            | 122 |
| Figure 4.5. Speed limits in Experiment 9.....  | 123 |
| Figure 5.1. The space-time diagram of sushi trays.....                               | 136 |
| Figure 5.2. Schematic of the displays in Experiment 10.....                          | 140 |
| Figure 5.3. The trial procedure for all experiments in Chapter 5.....                | 142 |
| Figure 5.4. Data and psychometric fits with Speed in Experiment 10.....              | 144 |
| Figure 5.5. Data and psychometric fits with Temporal Frequency in Experiment 10..... | 144 |
| Figure 5.6. Results of Experiment 10 for Averaged Performance .....                  | 145 |
| Figure 5.7. The capacity-one benchmark prediction.....                               | 153 |
| Figure 5.8. Schematic of the displays in Experiment 11 .....                         | 155 |
| Figure 5.9. Data and Psychometric fits in Experiment 11 .....                        | 157 |
| Figure 5.10. Data and Psychometric fits in Experiment 11.....                        | 157 |
| Figure 5.11. Results of Experiment 11 for Averaged Performance.....                  | 158 |

|  |            |
|--|------------|
| <i>Figure 6.1. Cartoon representation of tracking resource mediating speed limits and temporal frequency limits.....</i> | <i>189</i> |
|--|------------|

## List of Tables

---

|   |            |
|---|------------|
| <i>Table 3.1. Estimated lapse rates for different separations and targets in Experiment 7.....</i>        | <i>97</i>  |
| <i>Table 4.1. The five conditions of Experiment 9.....</i>  | <i>118</i> |
| <i>Table 5.1. Estimated lapse rates for different number of objects and targets in Experiment 10.....</i> | <i>150</i> |
| <i>Table 5.2. Estimated lapse rates for different number of objects and targets in Experiment 11.....</i> | <i>159</i> |

## Chapter 1 : General Introduction

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In our daily lives, we pay attention to specific tasks like browsing a website, speaking with a friend on the phone, or following the instructions of a coach. Even still, many of us have no profound understanding of what “attention” means or how the process of “paying attention to something” works in our brain. Attention is usually considered to be a limited-capacity resource that processes environmental stimuli. While early sensory stages (like the retina) process incoming information regardless of attentional state, later processes are directly affected by how much attention is allocated to processing.

The attentional capacity limit causes poorer processing when more task-relevant incoming information is added. If the quality and processing speed does not deteriorate when more information must be processed, no attentional capacity limit is present (Huang & Pashler, 2005). When more attentional tasks must be simultaneously executed, more task-relevant incoming information must be processed at the same time. Previous researchers frequently investigated the attentional capacity limit using dual-task experiments (Pashler, 1994; Pashler & Johnston, 1998).

In dual-task experiments, people often perform worse on a task when they try to execute a second task at the same time (Duncan, 1980; Norman & Bobrow, 1975). Performing binary tasks while sharing the same limited-capacity attentional resource imposes a cost on performance. Hence, people perform better on one task and worse on the other according to limited-capacity attentional resource.

In place of dual-task experiments, this thesis specifically studies the workings of attentional capacity with regard to the processing of incoming information by investigating the ability to process multiple objects or stimuli. Due to a limited attentional capacity, it is hypothesized that performance during the processing of multiple objects or stimuli will be worse than that of processing only one object. We investigate this hypothesis by asking

participants to track multiple moving objects. People usually have experience with the attentive tracking of objects in a dynamic environment. For example, when driving on a busy road we need to keep track of multiple moving objects around us, such as a dog or a child running across the street, while also noting other moving cars near us, in order to avoid hitting them. This tracking event is theorised to require our attention on those moving objects (Drew, McCollough, Horowitz, & Vogel, 2009). Therefore, to understand the mechanism of attentional resource allocation among targets, investigating with the task of object tracking is an appropriate approach.

In this chapter, the introduction of the subsection titled “*Understanding the Attentional Process*” and “*Resource Theory*” are presented first. After that, I review selected postulates of multiple object tracking literature, and some possible theories explaining the limitation of attentive tracking. Finally, the research questions of this thesis are summarised.

### **1.1 Understanding the Attentional Process**

In 1890, William James described attention in his book *Principles of Psychology*: “*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. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatterbrained state*” (James’s, 1890).

Three principal concepts of attention arise from James’s description. To begin with, when we pay attention to something, our consciousness is on this focal object with effort, and we feel that this processing costs mental energy (effort). Secondly, attention allows us to selectively process the huge amount of information that we encounter each day (selectivity). Because of the selectional process, we can attend to and interpret something relevant to us



while ignoring irrelevant information. The “cocktail-party problem” further illustrates the successfully working selectional process, because while at a cocktail party, one guest can listen to a particular conversation and apparently disregard other conversations (Cherry, 1953). Finally, selective processing is required because central processing has a limited capacity, which is why we cannot pay attention to all the details of the stimuli within our environments (capacity limitation).

Limited capacity is a core aspect of the theories of attention. Previous investigations about the attentional capacity limitation commonly used dual-task experiments (Pashler, 1994; Pashler & Johnston, 1998). The capacity limitation results of these experiments demonstrated that the performance of a first task is harmed by adding a second task. For the sake of interpreting the capacity limitation on dual-task experiments, Pashler (1994) outlined the three most influential models: cross-talk theory (Kinsbourne, 1981), central bottleneck theory (Broadbent, 1958), and resource theory (Kahneman, 1973). Unlike dual-task experiments, this thesis investigates whether a substantial cost on performing just one multiple object tracking (MOT) task occurs when additional targets are added, because of capacity limitation. To this end, these three influential models might also be able to explain the capacity limitation on object tracking via adding targets instead of tasks. The subsequent paragraphs will first introduce cross-talk theory, followed by the central bottleneck theory. Finally, resource theory will be described in detail.

According to cross-talk theory, capacity limitation results from the similarity between the cortical representations of two tasks, which is also termed the functional cerebral distance model (Kinsbourne, 1981). Different parts of the cortex are dedicated to different specific functions or behaviours, and each task may be mediated by a specific area of cortex. If two tasks are processed in a similar area of cortex, cross-talk will occur, which will subsequently lead to significant interference between the two aforementioned tasks. For example, the voice

control and motor control of the right hand are both mediated by the left cerebral cortex, whereas the motor control of the left hand is mediated by the right cerebral cortex.

Kinsbourne and Hicks (1978) measured the rates of voice-hand interference in professional pianists and demonstrated more interference between voice and right-hand playing than between voice and left-hand playing. Another example of cross-talk theory can be found in the fact that observers perform worse when we ask them to do a task controlled by unilateral limbs (right arm and right leg/ left arm and left leg) than when asked to perform tasks controlled by bilateral limbs (the two arms / the two legs). This is because the similarity of mental representation is statistically significant when performing with limbs controlled by the unilateral hemisphere (Kinsbourne, 1974).

Central bottleneck theory assumes that our attention can only operate on one task at a time. When two tasks are required to process at the same time, one task's performance will be delayed (Broadbent, 1958; Deutsch & Deutsch, 1963). Over the past few decades, experiments conducted with the psychological refractory period (PRP) task have elaborated upon the notion of the central bottleneck theory (Pashler, 1994; Pashler & Johnston, 1998). The response to the second task becomes slower when the interval between the first and second task is reduced, because the second task can only be processed after the first task is finished. When the difficulty of the first task is increased, this increases the response time for both the first and second tasks. Increasing the difficulty of the second task will have no effect on the first task.

According to the central bottleneck theory, the mind contains only a single "device" that is capable of carrying out one task at one time. Contrasting cross-talk theory, this processing device as stated by central bottleneck theory, may be mediated by the subcortical structures instead of the cortexes (Pashler et al., 1994). Pashler et al. (1994) demonstrated that for split brain patients as well as normal participants, the processing of one stimulus in one hemifield

(Task 1) delayed processing another stimulus in the opposite hemifield (Task 2). These results indicated the central bottleneck theory is not mediated by cortex, because for split-brain patients, each hemisphere independently processes the stimulus of the corresponding visual hemifield and does not influence the processing of the opposite hemifield.

## **1.2 Resource Theory**

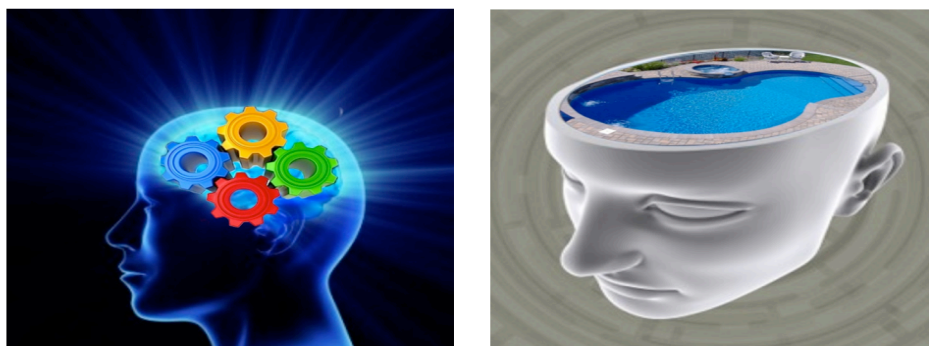
### **1.2.1 What is Resource Theory?**

Resource theory proposes that processing capacity can be shared among tasks, with more than one task simultaneously conducted. The distinction from the central bottleneck theory is that resource theory allows for a parallel division of attention. With central bottleneck theory, only one thing can be processed at a time- which means that tasks are processed serially (Kahneman, 1973). According to resource theory, people can process several tasks at the same time, but the performance of each task is impaired because less attentional resource is allocated to each task.

Imagine limited capacity as a swimming pool in our brain (Figure 1.1). The attentional resource resembles the water that is contained within this pool. A variety of attentional tasks and processes share this resource pool. To make this abstract theory more concrete neuroscientifically, one corresponding neural theory is that the pool is of neurons in our brain assigned to tasks depending on the task's demands. One possibility is that each task receives 50% of the total number of neurons when doing two equal-difficulty tasks at the same time. When the difficulty of the two tasks differs, one task is allocated more neurons than the other, like in the allotment distribution: 60%: 40%. As the number of simultaneous tasks increases, the number of neurons assigned to each task decreases, reducing the performance for each.

An oscillatory neural network model provides an alternative explanation for the resource theory (Kazanovich & Borisyuk, 2002, 2006). The oscillatory neural network

includes two main components: central oscillators (COs), which are assembly of neurons that represent the central executive of the attentional system in frontal-parietal networks, and peripheral oscillators (POs), which are an assembly of cortical neurons in visual cortices. The location of the tracking foci is formed by synchronous oscillations of these COs and POs, consistent with evidence that increased attention increases synchrony in visual cortex (Fries, Reynolds, Rorie, & Desimone, 2001; Womelsdorf, Fries, Mitra, & Desimone, 2006). When attending to a target, an assembly of cortical neurons related to the target (PO) works synchronously with an assembly of neurons that represents the central executive (CO) in a particular part of phase space. Attending to an additional target is mediated by oscillation at a different phase. The limited phase space can explain the limited capacity in simultaneously attentional processing, according to other theorists as well (Fries et al., 2001; Jensen & Lisman, 1998). As the number of targets increases, the angle between their phases decreases, increasing interferences so that they are less likely to maintain their coherent oscillation for the corresponding target only. In the particular model of Kazanovich and Borisyuk (2006), capacity is also limited by the number of POs. The POs consist of a limited number of layers, and each layer mediates a specific tracked target. Thus, the limited capacity of attentive tracking targets reflects dual constraints, both the maximum number of layers in POs, and the limited availability of phase space.



**Figure 1.1** *Cartoon representation of slot theory and resource theory*

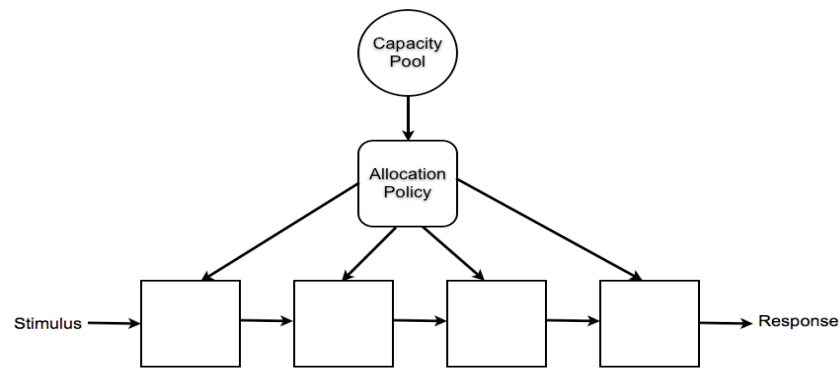
In the left panel (slots theory): the attentional capacity consists of four attention slots (gears), and each slot is responsible for one attentional task. In the right panel (resource theory): the attentional capacity is depicted as a swimming pool in our brain. Attentional tasks can use differing amounts of this resource (the pool water).

### **1.2.2 The History of Resource Theory**

Competing theories of attention were fiercely debated when resource theory was developed in the 1960s. Early selection theory proposed that attentional selection occurs before the semantic analysis of stimuli, and was based on the evidence that sensory selection was commonly more accurate and less effortful than semantic selection (the “filter theory” proposed by Broadbent, 1958). Cherry (1953) supported the early selection theory. In dichotic listening tasks (where two streams of speech were simultaneously fed one to each ear and asked participants only to attend to one ear) semantic contents and individual words were unnoticed, yet participants could report the gender of the speaker, speaking accents, and pitches within the unattended speech stream (Cherry, 1953).

Dissimilarly, late selection theory proposed that attentional selection took place after the semantic analysis of the stimuli. This theory also proposed that stimuli inputs could be identified and categorized by pre-attentive processes in parallel, without attention involved. This was supported by the finding that irrelevant stimuli were not excluded by early selection processing, and still underwent semantic analysis (Deutsch & Deutsch, 1963; Johnston & Dark, 1986; Moray, 1959).

Resource theory emerged to resolve the controversy between early selection and late selection theory by simply removing attention from the specific stage of information processing that goes from stimuli to response. Attention was a “mental energy” source that activated multiple processing stages differently via an “allocation policy”. Attentional selection could arise at any stage, early or late (Kahneman, 1973). Allocation policy was determined by the subject’s estimate of task demands, and a complex task imposed more demands than an easy task (Figure 1.2). Due to the resource being limited, performance deteriorates when the supply of the resource does not meet the total demands.



**Figure 1.2. Schematic description of resource theory**

The limited capacity of the resource pool supports attention selection with the allocation policy. The allocation policy determines how many resources are allocated to each processing stage from stimulus to response.

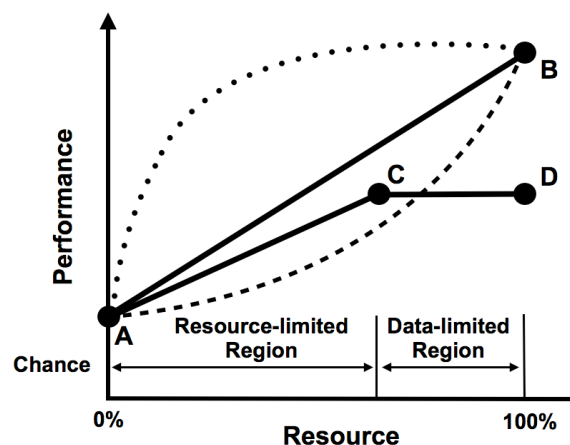
To further explain the resource theory of attention, three main characteristics are overviewed in the following sections. Firstly, attentional resource allocation to each task or target is continuous and gradual, like pouring juice into cups rather than distributing the boxes of juice. Secondly, the capacity of resource is limited so that you cannot get an infinite amount of juice. A final possibility in resource theory is that humans are able to flexibly distribute differential amounts of resource (juice) to distinct tasks or targets (cups). For example, one might devote 70% of the resource to one task or target and 30% to another.

### **1.2.3 First Characteristic of Resource Theory: Continuously Allocated Resource**

Resource theory proposes that resource is allocated in a continuous and graded approach, and that performance rises as a function of the amount of resource deployed (Kahneman, 1973; Logan, 1997). This allocation approach is different from the slots theory (Figure 1.1), where attention is discretely distributed with several fixed-size boxes or cups. As a demonstrative analogy for the slots theory, consider each slot as a pre-packaged boxed juice of a fixed size. The attentional capacity is composed of many fixed-size juice boxes, yet each task can receive only one juice box (slot), even when only a solitary task is processed. In this case, performance of the attentional tasks is determined by the number of slots we have. Earlier literature suggested that the limited number of slots is four. Performance declines when the task demand exceeds the maximum number of slots (Barton, Ester, & Awh, 2009;

Luck & Vogel, 1997; Rouder et al., 2008). In the slots theory, it is impossible to differentially allocate attentional capacity between multiple tasks or targets. Attention however, is allocated within arbitrary portions of the resource according to resource theory.

The resource-versus-performance function (RPF) described by Norman and Bobrow (1975) paper is an important concept of resource theory. This function may contain two major regions: a “resource-limited” region and a “data-limited” region (as shown in Figure 1.3). In the data-limited region, performance is independent of resource allocation (shown on the graph as a horizontal line segment between point C and D). Variation in the allocation of resources has no effect on performance in this region. When data-limited, the process is restricted by the quality of the data structure or data inputs, such as detection of a weak signal in a noisy environment.



**Figure 1.3. The resource-versus-performance function**

Performance is related to the amount of processing resources allocated. When 0% of resource was allocated, observers performed at chance level (point A) whereas the maximum performance was found when allocated all resource to the task (point B). The straight line connecting between point A and B is a linear resource-versus-performance function, which only has a resource-limited region. Another gentler slope function includes both data-limited region, which is a line segment between point C and D, and resource-limited region, which is connecting between point A and C. The data-limited region shows increasing the allocation of resources has no effect on the performance. In contrast, the performance improves with increasing amount of allocated resource in the resource-limited region. The dotted curve shows a RPF of less difficulty task than the dashed curve without linear relationship.

In the resource-limited region, an increase in the amount of resource allocation can improve performance. This is shown by a curve or a line with a positive slope. Figure 1.3 illustrates many possible relationships between task performance and resource deployment. A

linear relationship between performance and resource deployment is shown with a black straight line connecting between chance performance (point A), which is 0% resource deployment, and maximum performance (point B), which is 100% resource deployment. The line segment between point A and C is another linear RPF, which has a more gradual slope than the line segment between point A and B. To have an equal improvement in performance, the steep slope of RPF needs less resource deployed than the gentle slope of RPF. Due to data limitation, performance remains constant between point C and D, even if the amount of resource allocation is increased. The two curves showed RPFs of distinct difficult tasks, contrary to the linear relationship: the task of the dotted curve is much easier than that of the dashed curve. For the dotted curve, allocating minimal resource can improve performance to reach the ceiling level. For the dashed curve, even when allocating most of the resource, the performance does not improve much. All RPFs interpreted resource allocation is continuous and graded.

#### **1.2.4 The Second Characteristic of Resource Theory: Limited Capacity**

A second aspect of resource theory is that information processing has a limited capacity which can be divided among several concurrent processes. Under this assumption, most applications of resource theory are focused on explaining dual-task performance. If attentional capacity is unlimited, performance of one task is unaffected by the other task (Townsend & Ashby, 1983). In contrast, due to limited attentional capacity, performance substantially decreases with additional tasks. Similar to the progression which occurs with multiple tasks, processing various stimuli or objects also shares the same limited attentional resource. When two visual objects are presented simultaneously and briefly, typically reporting the visual properties of both objects is more difficult than only reporting the properties of either one alone (Alvarez, Horowitz, Arsenio, Dimase, & Wolfe, 2005; Duncan, Ward, & Shapiro, 1994).



Capacity limitations are supported by the finding that the performance of one task is adversely affected by the other task. The allocation of resource results in an increase in reporting accuracy for one task, with a decrease in accuracy for the other (Norman & Bobrow, 1975). The speed and accuracy of each task will be limited by the amount of resource the tasks are allocated (Kahneman, 1973).

An example of one context where resource theory has been useful is the psychological refractory period (PRP) paradigm. The PRP is a period that does not respond to any other tasks while one task is being processed. Its effect is usually shown by the fact that the response to the second stimulus becomes slower when the interval between the first and second stimuli is reduced (Telford, 1931). Although earlier studies showed the most prominent explanation of the PRP effect is provided by the central bottleneck theory (that only one task can process at a time) (Pashler, 1994; Pashler & Johnston, 1998; Welford, 1952), some exceptions of the PRP effect were found from later studies that the central bottleneck theory cannot explain, but that resource theory can (McLeod, 1977; Navon & Miller, 2002; Tombu & Jolicoeur, 2003). For example, the presence of the second stimulus lengthens the response time of the first stimulus. The difficulty of the first or second stimulus has a considerable effect on performance of the other stimulus. An increase in the difficulty of the second stimulus elongating the response time of the first stimulus, is because the second stimulus consumes more resource as difficulties increase. Due to limited capacity, less resource is allocated to process the first stimulus and therefore it increases the response time of the first stimulus. If capacity is unlimited, there should not be any effect on performance of the first stimulus (McLeod, 1977; Tombu & Jolicoeur, 2003).

### **1.2.5 Third Characteristic of Resource Theory: Flexible Allocation of Resource**

The flexible allocation of resource is a third issue for resource-intensive tasks. How is attentional resource allocated among a number of simultaneous tasks? One possibility is that,

among a set of simultaneous tasks, they all receive the same amount of attentional resource. Another possibility is that some tasks receive more resource than others (Bourke, Duncan, & Nimmo-Smith, 1996).

Several previous pieces of literature related to the dual-task experiment have shown that attentional resource can be flexibly allocated to each task, and that an increase in the performance of one task decreases the accuracy of the other (Morey, Cowan, Morey, & Rouder, 2011; Pastukhov, Fischer, & Braun, 2009; Sperling & Melchner, 1978). Morey et al. (2011) examined the performance of two concurrent tasks (a tone-sequence comparison task and a visual array comparison task) and manipulated the financial rewards to encourage participants to allocate different amounts of attentional resources to either task. Better performance was found in a tone-sequence task when participants were instructed with higher financial rewards for greater accuracy in that task, and vice versa when the rewards were greater for the other task. These results indicated that attentional resource could be flexibly allocated to different tasks according to intentions.

Besides participants voluntarily distributing distinct amount of resource to tasks, the resource allocation can be manipulated by the experimenter's emphasized instructions. When the emphasis placed on the two tasks is varied, performance is better on the emphasized task and worse on the de-emphasized task (Pastukhov et al., 2009; Sperling & Melchner, 1978). Pastukhov et al. (2009) concluded that visual attention is a single, integrated undifferentiated resource by measuring performances on four pairs of visual discrimination tasks. One central discrimination task was common to every pair while the other peripheral discrimination tasks (colour, colour-position, motion direction and motion) were varied. Discrimination priorities were manipulated in all pairs of the experiments, and observers were instructed to emphasize accuracy on a central task, a peripheral task, or both tasks. A trade-off between central and peripheral performance was found on all pairs of visual discrimination tasks. When the

central task had its highest performance, the other peripheral task was performed at or near chance rate. This implied that the central task required full attentional resource. However, while peripheral tasks were performed at or near 100%, the performance of the central task was varied with different pairs. In two pairs, the central task was performed at near 50% but in one pair the central task was performed better, with 75% correct. This implies that the attentional resource requirements varied for different peripheral tasks.

Brown, Collier, and Night (2013) also demonstrated that attention can be flexibly allocated between two concurrent tasks. Observers were instructed to execute two single tasks separately and to share attentional resource between the two tasks with three specified proportions: 75% for Task 1 / 25% for Task 2, 50% for Task 1 / 50% for Task 2, and 25% for Task 1 / 75% for Task 2. The performance of Task 1 showed a significant linear increase as resource allocation enlarged on Task 1, and a reversal of this linear effect was found upon performance of Task 2.

The flexible resource allocation above was also influenced by the demands of the task. A certain performance level is reached by allocating the required amount of resource to the task. Performance declines when the amount of allocated resource does not meet the required amount for that task. The effect of task demanding on attentional resource allocation is demonstrated in Tombu and Seiffert (2008) attentive tracking paper. Tombu and Seiffert (2008) asked observers to track multiple objects moving about the monitor and to discriminate whether a concurrently presented sound was of high, medium, or low frequency. The demand of the task was manipulated by increasing the speed of motion of the objects and the proximity between objects, with higher speeds and smaller proximities yielding a greater demand. During the tracking period, the performance of tone discrimination worsened considerably during the instant in which objects moved faster and were closer to other

objects. This result suggests that attentional resource is flexibly allocated to the tasks or objects that are more challenging.

### **1.2.6 Summary of Resource Theory**

In summation, resource theory considers the capacity limitations of executing multiple attentional tasks to be owed to a finite mental resource that can be flexibly and gradually be allocated to each task, depending on its demand.

In the past 25 years, around 2400 articles dealing with visual attention have been published. Most of these articles were focused on static attention, which can be described as the attentive process that occurs after people attentionally select a location or stationary object. These articles found that subjects' attention was maintained on the focal object or location throughout the processing (Carrasco, 2011). During the trial, the attention does not shift to other objects or locations (Hede, 1981; Posner, Snyder, & Davidson, 1980). Abundant empirical evidence has been provided which demonstrates that the deployment of attention over spatial locations or stationary objects is quite flexible and allows for attending to separate locations or stationary objects. At that juncture, the perception of stimuli at that location or stationary object can be improved (Awh & Pashler, 2000; Duncan, 1984; Egly & Homa, 1984; Malinowski, Fuchs, & Muller, 2007; McMains & Somers, 2004). However, these improvements on perception only exist at a specific location or stationary object. How is the attentional process of the stimulus quantified if the stimulus is moving during the process?

The multiple object tracking (MOT) paradigm introduced by Pylyshyn and Storm (1988) opened a new avenue for studying attention with regards to moving objects. In this task, people deployed attention to targets that continuously changed their locations throughout the trial and subjects were required to track those changes. As we know, attention allows us to process information regarding the properties or locations of objects, and to make

an appropriate response based on this information processing. For example, in order to avoid getting hurt, we stay far away from the firecrackers. Yet, if objects are moving, the ability to track them becomes vitally important for humans. A reduction in the ability to track objects significantly impairs daily functioning. Following the firecracker example, if the firecrackers were to fly around us rather than exploding in a specific area, we would have to track them with attention, and dodge them by moving our bodies. Studying the task of tracking multiple objects can make us understand more about how humans allocate our attention when the target stimuli are not stationary. In the following section, we will review literature related to the task of multiple object tracking, which has been a popular approach to research about visual attention within a dynamic visual environment.

Before entering the following section, here we specifically define the term “central attentional resource” and “tracking resource” to clarify what we mean by these two resources. In the aforementioned sections, the resource that is shared between tasks in all dual-task experiments is the central attentional resource. Each task receives part of central attentional resource to make its own specific resource. For example, different modalities of inputs (visual and auditory) may have their own resource (Wickens, 1980). In the study conducted by Tombu and Seiffert (2008), central attentional resource consists of a tracking resource and an auditory resource. When observers are asked to only execute one MOT task (instead of dual tasks) the central attentional resource should only consist of one tracking resource. In this thesis, we investigate the workings of the tracking resource to extendedly interpret the central attentional resource.

### **1.3 Multiple Object Tracking**

Maintaining attention on tracked objects is critical to our daily activities. To avoid getting hurt while walking on a busy street, we have to pay attention to multiple objects, such as a vehicle or dog approaching us, a ball rolling across our path, or a jogger running near us.

Additionally, previous literature demonstrated the ability of object tracking is important to understand the development of object knowledge in infants (Carey & Xu, 2001; Moore, Borton, & Darby, 1978), and for the improvement of biological motion perception (Legault & Faubert, 2012). Over the past two decades, more than one hundred papers were published regarding how our attention tracks multiple objects concurrently. Most of the papers related to multiple object tracking (MOT) have been focused on investigating the limited capacity aspect, which specifies that when the demands of the task are overloaded, observers easily lose the targets to be tracked.

### **1.3.1 Multiple Object Tracking (MOT) Paradigm**

In 1988, Pylyshyn and Storm developed the MOT paradigm in order to investigate how human beings simultaneously track multiple objects. This paradigm uses multiple objects wandering around on the computer monitor, and is by far the most common technique for studying multiple object tracking. In a typical experimental paradigm, a number of identical objects (squares, circles, or crosses) are presented on the computer monitor and a subset of these elements is cued (flash or change colour) for a few seconds as the targets to be tracked. The cues then disappear so that the targets are identical to non-targets. All of the objects independently and randomly wander about the screen for several seconds. The objects in some studies avoid colliding with other objects, but in other analysis the objects do collide, occlude, or bounce off each other. At the end of the trial, all of the objects stop moving and observers must indicate which objects are the targets. Participants respond to some cases by clicking all of the targets using a mouse. In other cases, one of the objects is probed and observers judge whether that object is a target or not by pressing a key.

With typical speeds, variation in spacing, eccentricities, and other popular settings for display parameters, the maximum number of targets that can be successfully tracked is around four (Culham, Cavanagh, & Kanwisher, 2001; Pylyshyn & Storm, 1988; Scholl,

Pylyshyn, & Feldman, 2001; Yantis, 1992). Different theories explain this limitation in different ways.

### **1.3.1.1 Spatial interference theory**

Franconeri and his collaborators suggested that spatial interference is the only factor that limits the number of targets that can be tracked, writing that “barring object-spacing constraints, people could reliably track an unlimited number of objects as fast as they could track a single object” (Franconeri, Jonathan, & Scimeca, 2010, p. 924). A decrease in tracking performance with additional targets was theorised to be owed to the cortical representations of two nearby targets interfering with one another (Franconeri, 2013). Specifically, when two targets are close to each other, a suppressive surround of one target may overlap with the spotlight of attention focused on the other target and vice versa, yielding worse tracking performance for both targets (Franconeri, 2013; Franconeri, Lin, Pylyshyn, Fisher, & Enns, 2008). Spatial interference undoubtedly can contribute to the capacity limit when traditional MOT displays are used, because in those displays objects pass very close to each other, which can cause crowding (Intriligator & Cavanagh, 2001; Pelli & Tillman, 2008). This theory is similar to the cross-talk theory in dual-task experiments.

According to the spatial interference theory, lower tracking performance at higher speeds (or a larger number of tracked targets) results from the increased number of times that the objects come close to each other. Franconeri et al. (2010) suggest that the critical factor limiting tracking performance is the accumulated distance that objects travel. Longer total travel distance led to more occasions of close proximity among objects and subsequently decreased the tracking performance.

Rather than capacity limits being imposed by spatial interference, most published theories claim that capacity limits are instead caused by a finite mental resource that the

targets consume. The following sections will individually introduce three main theories related to mental resource: slots theory, serial switching theory, and flexible resource theory.

### **1.3.1.2 FINST (slots theory)**

FINST (FINgers of Instantiation, abbreviated as “FINST”) is a model to explain visual capacity limits in terms of a fixed number of slots. Pylyshyn and Storm (1988) propose that multiple object tracking is accomplished by FINSTs. The original claim of the FINST theory is that several pre-attentive indexes independently “stick” to or point to multiple tracked objects while maintaining contact with those objects throughout the motion period. The FINST does not encode any properties of the feature and simply makes it possible to locate the feature. Therefore, tracking multiple moving objects with FINSTs does not result in recognizing their features or encoding the relationship between features and locations (Pylyshyn, 1989). For example, while participants successfully tracked the locations of targets, they failed to match non-spatial properties (such as colour and shape) to the correct locations (Pylyshyn, 2004). As for the capacity limits, the proposal of the FINST theory maintained that limited tracking performance arises from a finite number of those “indexes”.

Many researchers now broadly explain the FINST theory as a fixed-resource theory of visual capacity limits (Bae & Flombaum, 2012; Trick, Guindon, & Vallis, 2006). Our attention has a small number of discrete buffers, FINST, or slot-like representations, and a significant capacity limit occurs when we try to process more objects than available representations (Drew & Vogel, 2008). As an analogy for the FINST or slots theory, consider each slot as a pre-packaged boxed resource (juice) of a fixed size. The maximum number of targets we can track are determined by how many pre-packaged juice boxes (slots) we have. Tracking performance will decline when the number of tracked targets exceeds the maximum number of juice boxes.



#### **1.3.1.3 Serial switching theory**

An extreme variant of the slot theory posits that only one slot or spotlight is available, and it must be rapidly switched among targets for tracking to succeed (Oksama & Hyona, 2008; Tripathy & Howard, 2012; Tripathy, Ögmen, & Narasimhan, 2011). Oksama and Hyona (2008) termed this model the MOMIT (Model of Multiple Identity Tracking), whereas S. P. Tripathy et al. (2011) termed it the MTT (Multiple Trajectory Tracking) model. Here, we call the term the “serial switching theory”, which resembles the central bottleneck theory in dual-task experiments.

According to serial switching theory, each target is attended to in turn and target positions are updated one by one. When it is time to re-attend to a given target, whichever object is closest to the target’s previously registered position is assumed to be the target. When there are more tracked targets, the position of each is updated less frequently (Howe, Cohen, Pinto, & Horowitz, 2010; Tripathy et al., 2011), resulting in more occasions where we lose the tracked targets because the targets travel farther in each position update. This is the reason for the capacity limits.

#### **1.3.1.4 Flexible resource theory (FLEX theory)**

Alvarez and Franconeri (2007) proposed a flexible-resource theory, which embodies the idea that attentional capacity is a continuous resource and the tracking limitation depends on the resource demands, rather than a fixed number of slots or FINSTs. One target travelling at high speeds or near a distractor may be more difficult to track, and under such circumstances, allocating additional tracking resource might compensate for the difficulty.

In this theory, the maximum number of targets to be tracked is decided by flexible indexes (FLEXs) instead of FINSTs. Unlike FINSTs, it assumed that there is no numerical limit to the number of FLEXs that can be deployed. The availability of a finite resource determines how many FLEXs can be created for tracking targets, and the spatial or temporal

resolution of each FLEX. The spatial or temporal resolution for each target is lower when more objects are tracked. Thus, the flexible-resource theory explicitly predicts that the faster the objects move or the smaller the distance between objects, the fewer will be tracked. As an analogy for the flexible resource theory, consider FLEXs as cups and a finite resource as a bottle of juice. The more cups we serve, the less juice each cup has. Tracking performance (resolution) for each target (cup) is determined by how much juice it has. This theory resembles the resource theory in dual-task experiments.

### **1.3.2 Debate among the Four Theories**

The explanation of the capacity limitation of tracking has been debated with these four theories we mentioned above. Serial switching theory proposed that humans only have a single attentional spotlight and during the tracking period, this spotlight quickly switches among tracked targets (Oksama & Hyona, 2008; Tripathy & Howard, 2012; Tripathy et al., 2011). However, Pylyshyn and Storm (1988) argued that capacity limitations exist because we possess only a limited number of discrete mental pointers (FINSTs), and proposed that tracking multiple moving objects should be in parallel. Pylyshyn and Storm (1988) assumed that attention takes longer to switch among locations or objects that are further apart, and then suggested a spotlight would require switching at an implausibly high rate to explain their data. In contrast to these findings, many studies have discovered that attention does not take longer to shift across larger distances (Kwak, Dagenbach, & Egeth, 1991; Shih & Sperling, 2002). Tripathy et al. (2011) further pointed out that the traces of the moving objects are likely transiently recorded in the iconic memory buffer, facilitating target recovery in the traditional MOT task. Therefore, the help of an iconic memory buffer allows serial switching to more plausibly explain tracking data.

Alvarez and Franconeri (2007) proposed a flexible resource theory of tracking and found evidence that tracking accuracy declined gradually with increasing numbers of targets,

rather than dropping catastrophically as predicted by slots theories such as FINST. Based on the FINST theory (Pylyshyn & Storm, 1988), performance should be equally exceptional for all target numbers fewer than the number of FINSTs. When no more indexes or slots are available as the target number increases, performance should drop catastrophically, rather than decrease gradually. In their experiments, Alvarez and Franconeri (2007) found that at high object speeds, observers could track only one target, but as the object speed was decreased, their observers were able to track more targets. At very low speeds, their observers could track up to eight targets, far greater than the four to five target maximum predicted by the FINST model.

In recent years, Franconeri and colleagues have argued that tracking multiple objects is not mediated by mental resource, and that tracking capacity is affected only by spatial interference between targets (Franconeri et al., 2010; Franconeri et al., 2008). The first purpose of this thesis is to investigate this hypothesis. In experiments that avoid the confound of spatial interference, (located in Chapter 2) we examine whether tracking multiple objects is mediated by a tracking resource, leading to a substantially worse performance with additional targets.

If we find that tracking multiple objects is mediated by a tracking resource in Chapter 2, then how does our brain act like a resource? The brain is divided into separate right and left hemispheres that are connected by the corpus callosum. As we know, visual stimuli are processed first by the contralateral visual cortex, with the right visual cortex processing the inputs from the left visual hemifield. The left visual cortex processes the input from the right visual hemifield. In multiple object tracking, performance might be mediated by two independent hemisphere-specific resources rather than a general central resource (Alvarez & Cavanagh, 2005). The resource in the left hemisphere tracks the stimuli in the right visual hemifield and the resource in the right hemisphere tracks the stimuli in the left visual

hemifield. In the following section, the hemisphere-specific resource theory of object tracking will be reviewed.

#### **1.4 Hemisphere-specific Resource Theory**

Previous studies have suggested there are independent attentional resource pools in the left and right cerebral hemispheres of split-brain patients, inducing a faster processing of a visual search task in bilateral displays than in unilateral displays (Luck, Hillyard, Mangun, & Gazzaniga, 1989). Each hemisphere can process information independently with its own resource (Friedman & Polson, 1981). For neurologically intact observers, converging evidence for two independent hemispheric resources come from several research areas: multiple object tracking (Alvarez & Cavanagh, 2005), target identification (Awh & Pashler, 2000; Nishimura, Yoshizaki, Kato, & Hatta, 2009), visual working memory (Delvenne, 2005; Delvenne & Holt, 2012; Umemoto, Drew, Ester, & Awh, 2010), and neuroimaging studies (Pollmann, Zaidel, & von Cramon, 2003). Performance of the aforementioned tasks was better when stimuli were distributed across the left and right visual hemifields than for when they were all displayed within the same hemifield.

Within the context of tracking, Alvarez and Cavanagh (2005) provided compelling evidence of independent resources for attentive tracking in the bilateral visual hemifields. They presented two targets in one visual hemifield and tested the effect of adding another two targets in the same hemifield or in the opposite hemifield. Performance was much poorer when the additional targets were presented in the same visual hemifield, but not affected much when the target was presented in the opposite hemifield. This suggests that the resource consumed by additional targets is hemisphere-specific.

A concern with the Alvarez and Cavanagh (2005) finding was that it was not clear how much of the effect was resource related and how much was owed to crowding. Clearly, crowding effects can play a role in object tracking (Chakravarthi & Cavanagh, 2009). Objects

that pass close together can be hard to individuate, which can result in a decrease in tracking accuracy (Intriligator & Cavanagh, 2001). In the Alvarez and Cavanagh (2005) study, objects could pass very close to each other. Since crowding effects are known to be greater when objects are presented unilaterally rather than bilaterally (Liu, Jiang, Sun, & He, 2009), the observed decrease in tracking performance when the objects were presented unilaterally may have been owed to crowding. The purpose of Chapter 3 is to investigate whether the hemisphere-specific resource is also consumed by increasing speeds when crowding and spatial interaction effects are minimized.

According to the flexible resource theory (Alvarez & Franconeri, 2007), when more targets are present, each receives a proportionately smaller share of the tracking resource. The faster an object moves, the more resource is required to track it. Assuming that humans have a finite mental resource, this theory proposes that the faster objects move, the fewer can be tracked. Alvarez and Cavanagh (2005) already found that resource consumed by additional targets is hemisphere-specific, and here we explored whether increasing target speeds also consumes these two independently flexible hemisphere-specific resources.

The results described in Chapters 2 and 3 support the theory that tracking objects is mediated by a tracking resource by excluding the concern of spatial interference. Flexible allocation of resource is also a possibility for resource theories. In order to demonstrate that tracking resource is the main contributor affecting tracking performance, it is better to explore whether tracking resource can be flexibly allocated between targets or tasks. In the following section, the renewed literature will focus on the flexible resource allocation of multiple object tracking.

### **1.5 Flexible Resource Allocation related to Multiple Object Tracking**

Dual-task experiments have been a primary theoretical approach in the researching of human attentional performance limits, and may provide insight into how attentional resource

is flexibly allocated between two tasks. Researchers have provided evidence that a limited attentional resource is flexibly shared between the MOT task and various secondary attentional tasks, specifically a visual search task, sequential finger tapping task, and auditory discrimination task (Allen, McGeorge, Pearson, & Milne, 2006; Alvarez et al., 2005; Tombu & Seiffert, 2008; Trick et al., 2006). Allen et al. (2006) investigated this by pairing a MOT task with either a visual/verbal digit categorization task, an auditory/verbal digit categorization task, an articulatory suppression task, or a spatial tapping task. Evidence for sharing a central attentional resource was demonstrated by the significantly poorer performance on MOT in the dual-task condition than in the single-task condition. Specifically, performance for the MOT task was significantly poorer when carried out with the visual/verbal digit categorization task than when carried out with the spatial tapping task. Trick et al. (2006) also demonstrated that observers perform better with a sequential tapping task, in which they repeatedly tapped the little finger, middle finger, and thumb of their non-dominant hand in order, than an articulation task, in which they repeatedly pronounced three different syllables in order, when pairing with a MOT task separately. From such interference between tasks, one possible explanation is that observers could flexibly allocate different amount of resource to different tasks, with more resource to the one task relative to the other task when pairing with a MOT task simultaneously. Some researchers might argue this differential interference is simply because some tasks interfere more with the MOT task than other tasks.

A central piece of evidence that demonstrates the involvement of attentional resource in tracking for flexible resource allocation was provided by Tombu and Seiffert (2008). Tombu and Seiffert (2008) devised a way to investigate the attentional demands of tracking in detail. The secondary task was auditory discrimination. The attentional demands of tracking were manipulated by increasing the tracking difficulty, with higher target speeds and

proximities expected to require more attentional resource. During the tracking period, a transient increase in dot speed of about 60% or a transient decrease in inter-dot distance of about 45% was randomly applied to manipulate the attentional demands. The worst performance was expected when targets moved at high speeds at the same time that the sounds to be discriminated were presented. Results showed that increasing the object speed reduced accuracy. This reduction in accuracy occurred by a greater amount when the speed increase coincided with the auditory stimuli. The smaller effect of speed in the absence of the auditory task may reflect an ability to compensate for the speed increase when attentional resources are available. These experiments not only indicate that a central attentional resource was shared between the auditory task and the MOT task, but also suggest that resource allocation might depend on object speed, with faster targets consuming more attentional resource.

In the Tombu and Seiffert (2008) experiments, attentional allocation to the moving objects was only tested relative to an auditory non-tracking task. They demonstrated tracking task and non-tracking task are shared a common central attentional resource, which might consist of one tracking resource and one non-tracking resource. It remains unknown whether within the visual tracking task, where the central attentional resource is composed of only one tracking resource, the resource could distribute differentially to targets moving at faster speeds. The purpose of Chapter 4 was to investigate this.

From Chapter 2 through Chapter 4, we investigated whether a mental resource mediated the processing of tracking multiple moving objects by measuring the change in speed limits. Is any other factor that influenced tracking performance also mediated by the tracking resource? In the following section, we will briefly review another factor that is potentially mediated by tracking resource: temporal resolution of attention.

## 1.6 Temporal Resolution of Attention and Resource Theory

The temporal resolution of attention is evident from the experience of viewing a light alternating between on and off (He, Cavanagh, & Intriligator, 1997). Scientists measure the maximum temporal frequency (alternation rate) that observers can individuate successive states of light and quantify the temporal resolution of attention with this maximum temporal frequency. When the temporal frequency is over 7-10 Hz, the light is experienced as a constant flicker without discrete appearances and disappearances, which is termed *Gestalt* flicker fusion (Van de Grind, Grusser, & Lunkenheimer, 1973).

The temporal resolution of attention has been considered a major processing limitation during the flow of information from sensation to action (Marois & Lvanoff, 2005). A severely impaired processing is found when two targets are presented close together in time. Duncan et al. (1994) presented two to-be-attended stimuli in an ordered succession and measured how long the first stimulus continued to interfere with the second. They found that interference gradually declined when the interval between two stimuli was greater than 300ms. Duncan et al. (1994) concluded that the temporal resolution of attention for one stimulus might be around 300ms. In later studies using similar methods of rapid serial visual presentation (RSVP), researchers proposed that observers devote limited attentional resources to the first target at the expense of the second (Dux, Asplund, & Marois, 2008; Shapiro, Raymond, & Arnell, 1997; Vogel, Luck, & Shapiro, 1998). These studies found that an increase in the accuracy needed to identify the first target elongated the temporal lags between the first and second target. Under these circumstances the accuracy of the second target deteriorated considerably. These RSVP studies, however, support limited attentional resource sharing between targets with a biased approach. They cannot manipulate the amount of resource devoted to the second target to investigate whether it affects performance of the first target.



In the aforementioned studies, the performances limited by temporal resolution occurred when observers could not accurately identify static letters or pictures because the stimulus presentations were successively replaced at a particular location too quickly. In this thesis, the stimulus presentations are continuously updated their locations. Is performance of tracking multiple objects also constrained by the temporal resolution? In a situation we track a stimulus blob moving in a circular trajectory with one distractor located opposite the target blob in the trajectory. If both blobs move at the speed of 1 revolution per second (rps), after the target passes a location, the distractor passes by it 0.5 s later. If more distractors are added, evenly spaced about the trajectory, then after the target passes a location, a distractor will pass sooner than 0.5 s. If that interval is too short, observers may be unable to distinguish the target blob from the distractor blob, and therefore be unable to track. In this situation, the temporal resolution is defined as the minimum time needed between target and distractor blobs. Chapter 5 explains this in more detail.

In the context of tracking, only Verstraten, Cavanagh, and Labianca (2000) probed for a temporal resolution of attention limitation on tracking performance. In one display, several discs were arrayed in a circular trajectory about fixation. All the discs stepped (apparent motion) about fixation, and one of them was designated for tracking. In another display, a continuous radial circular sine wave grating was presented, centred on fixation. Participants were told to track an individual bar of the rotating grating. Verstraten et al. (2000) measured the temporal frequency limit (temporal resolution) by varying the object speed and the number of distractors within a circular trajectory and found a temporal frequency limit constrained tracking of a moving target. These results suggest that temporal resolution of attention can limit attentive tracking.

Verstraten et al. (2000) did not provide any evidence relevant to the relationship between flexible resource theory and the temporal resolution constraint of attentive tracking.

The purpose of Chapter 5 is to investigate this relationship. Previous literature demonstrated that temporal resolution for identifying two targets (e.g., letters) in a rapid stream may be influenced by attentional resource allocation (Dux et al., 2008; Shapiro et al., 1997; Vogel et al., 1998), with poor performance allocating less resource on that target. These studies can only manipulate the amount of resource allocation on the first target, instead of the second target. According to the flexible resource theory, more targets to be tracked leads to less resource allocated to each target. This might result in poorer temporal resolution.

### **1.7 Questions in this Thesis**

In order to address the issue of whether tracking multiple objects is mediated by tracking resource when crowding and spatial interference effects are minimized, Chapter 2 measured the change of the maximum object speed (speed limit) for tracking for different numbers of targets. According to the flexible resource theory, it is predicted that the speed limit for tracking one target should be considerably higher than that for tracking more targets. To determine whether spatial interference is the reason for this rather than resource, we vary the separation between two targets and then measure the difference of the speed limits.

The attentional tracking resource might be hemisphere-specific rather than a central global resource (Alvarez & Cavanagh, 2005). In Chapter 3, the hemisphere-specific resource theory is investigated by measuring the difference of speed limits between when targets were presented in bilateral hemifields and when targets were presented only in unilateral hemifield. It is hypothesized that the speed limit for tracking targets in one visual hemifield should not be significantly affected when one is required to track targets in the other hemifield. In contrast (compared to two targets in opposite hemifields), adding two more targets (one in each hemifield,) should have a large cost on speed limits.

In Chapter 4, we investigated whether the tracking resource could be distributed differentially between two targets in the same hemifield. If the tracking resource can be flexibly allocated to targets with different speeds, the fast target should receive more resource than the slow target. This predicts a higher speed limit for the fast target when two targets move with different speeds than when two targets move at equal speeds. Additionally, according to hemisphere-specific resource theory, differential resource allocation should not occur for two targets located in opposite hemifields.

Temporal resolution might be another constraint of attentive tracking (discussed more in Chapter 5). Observers lose the tracked target if distractors occupy a location close to the time a target occupies it. This is the situation when the target and distracter motion yield a high temporal frequency. In Chapter 5, we will investigate whether tracking performance is constrained by temporal frequency, and if the temporal frequency limit changes as the number of tracked targets are increased, as might be predicted by the flexible resource theory.

## **Chapter 2 : The Tracking Resource Theory and The Reduction in Speed Limit by Additional Targets**

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### **2.1 Introduction of Chapter 2**

Driving a car in crowded traffic and playing team sports may rely on the ability to simultaneously attend to multiple moving objects. The Multiple Object Tracking (MOT) task (Pylyshyn & Storm, 1988) has been widely used to study this process (Cavanagh & Alvarez, 2005; Scholl, 2009). With the MOT task, people typically succeed at tracking up to four or five targets (Culham et al., 2001; Pylyshyn & Storm, 1988; Scholl et al., 2001; Yantis, 1992).

As outlined in Chapter 1, debate over the explanation of this capacity limitation to tracking has led to four different accounts. Excluding the spatial interference theory (Franconeri et al., 2010; Franconeri et al., 2008), the other theories share a common concept that tracking performance is mediated by an attentional resource. These three theories differ in explaining how this resource is allocated. For the FINST (slot) theory, a tracking resource consists of several discrete slots, and each target receives one slot. For the flexible resource theory, a tracking resource is continuously and gradually allocated to each target, like pouring water into many cups, and more resource is allocated to the target that is more difficult to track. For the serial switching theory, tracking resource is allocated to one target at any given time, serially switching between targets. The subject of this chapter is not to address this difference, but rather to investigate whether limitation to tracking capacity is caused only by spatial interference, as suggested by Franconeri and his colleagues (Franconeri et al., 2010; Franconeri et al., 2008).

For the purpose of this chapter, we assumed that if tracking performance is not limited by spatial interference, it should be mediated by a tracking resource. There is some debate in the literature over the effect of speed. Evidence from Tombu and Seiffert (2008) indicates that transiently increasing object speed increases the attentional demand for tracking

accurately. In their experiments increasing the object speed reduced accuracy. This reduction of accuracy occurred by a greater amount when the speed increase coincided with an attentionally demanding auditory task. These results indicated that the demand of the auditory task and the demand of increasing object speed both share the same attentional resource. However, Franconeri and colleagues suggested that the decline in tracking performance with increasing speed was caused by greater spatial interference between targets at faster speeds, not by the speed itself (Franconeri et al., 2010; Franconeri et al., 2008). In Chapter 2, we will explore whether increasing speed consumes more attentional resource when we exclude the confound of spatial interference. In other words, the purpose of Chapter 2 is to investigate whether spatial interference is the only factor determining the decline in tracking performance.

### **2.1.1 Object Speed and Tracking Performance**

Using the MOT paradigm, Alvarez and Franconeri (2007) found that at high object speeds, participants can accurately track only a few objects, while at low object speeds, they can track several objects accurately. In a study by Bettencourt and Somers (2009), at an object speed of  $0.5^{\circ}/s$ , participants could track 6 objects, while at  $13^{\circ}/s$  they could track only 1 object (see also Liu et al., 2005). Effects of speed have usually been explained in terms of a flexible-resource theory of tracking. The trade-off between speed and the number of objects that can be tracked was interpreted as a common attentional resource shared between these two factors. When more targets are present, each receives a proportionately smaller share of the resource (Bettencourt & Somers, 2009; Liu et al., 2005).

### **2.1.2 The Proximity Confound**

In the aforementioned MOT studies, object speed is correlated with how frequently objects come near one another. Franconeri et al. (2008) developed much of this research

field, suggesting that the only reason that higher speeds are associated with lower performance is the greater number of times the objects come close to each other.

A number of results support the notion that objects very close together are more difficult to track (Drew & Vogel, 2008; Franconeri, Alvarez, & Enns, 2007; Shim, Alvarez, & Jiang, 2008). Unfortunately, these studies have not quantified the precise object spacing below in which tracking performance begins to decline. Some have parametrically varied the closest spacing by which objects approach each other (Carlson, Alvarez, & Cavanagh, 2007; Shim et al., 2008), but none have measured how the effect of spacing varies with eccentricity and angle. However, separate psychophysical literature has quantified a phenomenon called “crowding” (Pelli & Tillman, 2008; Strasburger, Harvey, & Rentschler, 1991) using tasks that involve identification of a single target. A rule that is usually accurate for two objects arrayed in the radial direction is that when they are closer than half their eccentricity (Bouma, 1970; Levi, 2008), perception of many aspects of each target is impaired. In these circumstances it seems that one cannot attentionally select the target without also selecting its neighbours (Bahcall & Kowler, 1999; Intriligator & Cavanagh, 2001). Intriligator and Cavanagh (2001) provided the first evidence that the critical spacing of attentional selection increased with increases in eccentricity.

For object tracking, performance may be limited by the same attentional processes as target identification (Pelli & Tillman, 2008) and selection (Intriligator & Cavanagh, 2001). If the target could not be selected from the nearby distractors owing to crowding, observers must have been unable to track targets successfully.

Due to the crowding phenomenon, the issue of whether there should be any effect caused by proximity is no longer in question. An issue is whether a proximity effect is the sole reason for the decline of tracking performance at higher speeds, as S. L. Franconeri et al. (2008; 2010) suggested. The first indirect support for this claim comes from a 2008 study

(Franconeri et al., 2008). These experiments involved two different-sized MOT displays, with the larger display as simply a four-fold magnification of the smaller display. The speeds of the objects in the larger display were thus four times higher than that of the small display. Despite the speed difference, tracking performance was similar for the small and large displays at all target set sizes used. This prompted Franconeri et al. (2008) to conclude that speed itself may not directly affect performance. However, speed was certainly not the only difference between the two conditions. Object speed and object crowding may have been different. Therefore, the conclusion that lower tracking performance occurs with increasing display set sizes (only because of greater crowding) is not convincing.

In a 2010 study, Franconeri and colleagues focused on the relationship between the proximity of objects in MOT and the total distance the objects travel during a trial. They pointed out that with greater cumulative travel distances in a typical MOT display, more occasions of close proximity among objects would occur. Their results showed that tracking accuracy dropped significantly with increasing cumulative travel distances. They suggested that the critical factor limiting tracking performance is the number of times that objects come close to each other (greater proximity) rather than the objects speed. However in their experiment 2, with conditions of equal cumulative travel distances, the one with the highest speed was significantly worse than other speed conditions on tracking performance. This is evidence for an effect of speed on tracking performance, but Franconeri suggested this speed effect resulted from the data limitation not resource limitation. The data limitation is caused by a poor quality of data inputs, such as detection of a weak signal of stimulus in a noisy environment, which is independent of the attentional resource deployment (Franconeri et al., 2010).

It remains uncertain whether higher object speeds will reduce tracking capacity when the confound of proximity is removed. In the following paragraphs, we investigate whether a

limited resource model can account for speed effects on tracking performance when the proximity effect is minimized. By this account, even if proximity is equated across speeds, more resource must be deployed to targets that are moving more quickly. Additionally, both an increase in number of targets and an increase in the speed at which these objects travel, place demand on the same attentional resource, and so object speed and the number of objects that can be tracked must trade off.

In the traditional MOT paradigm, objects are continually coming close to each other or moving away from each other, and proximity is not tightly controlled. Here, by using a paradigm more like that of Verstraten et al. (2000), we were able to control proximity and measure speed thresholds for each condition. In this chapter, Experiment 1 investigated whether higher speed limits are found for tracking one target than tracking two targets, and compared the tracking speed limit between large and small (potentially crowded) object spacing. In Experiments 2 and 3 the cumulative distance that objects travel was equated, and we tested whether tracking accuracy drops at faster speeds and speed limits decrease as more targets are tracked.

## **2.2 Experiment 1: Target Number Effect on Speed Limits**

As noted above, Franconeri and colleagues theorised that there would be no target number effect on tracking speed limits if objects did not pass near each other. The goal of our first experiment was to test for a target number effect on tracking speed limit in a situation where object-to-object spacing could be varied across conditions. Two conditions of object spacing were used, one in which the objects were always very far apart, and one where they were closer together and might crowd each other.

S. L. Franconeri et al. (2008) broadly applied the term “crowding” to describe the target proximity in their article. For clarity, we will reserve the word “crowding” to situations where psychophysical literature has validated that there will be interference among stimuli,



either because the interference on a perceptual task was measured, or because previous literature strongly suggested such interference should occur, as when the spacing between objects in the radial direction is less than half their eccentricity (Pelli, 2008). In the study of S. L. Franconeri et al. (2008) the MOT targets wandered randomly on the screen, with spacing not controlled relative to eccentricity. Here we used constant-eccentricity circular trajectories to better control spacing.

In Experiment 1, we used two concentric circular trajectories (rings) centred on fixation. Two objects were placed in each ring. The two objects of each ring were always on opposite sides of the circle ( $180^\circ$  of the circle apart). The inner ring had a radius measured at 2 degrees of the visual angle (deg). In the small-separation condition, the outer ring had a radius of 4 deg. In the large-separation condition, the outer ring had a radius of 9 deg.

In the small-separation condition, the closest that two blobs ever came to each other was 2 deg. This occurred when the two blobs were at the same point in their circular trajectory. The usual finding with crowding is that an object can crowd a target if it is separated from the target by less than half the target's eccentricity (Bouma, 1970; Pelli & Tillman, 2008). As the inner blob is separated from the outer blob by exactly half the outer blob's eccentricity, the inner blob is on the boundary of crowding the outer blob and therefore some crowding may occur. By contrast in the large-separation condition, the closest approach of the inner blob and outer blob is 7 deg, quite far from the expected 4.5 deg crowding zone. Overall, then, our expectation was that crowding might occur in the small-separation condition but not the large-separation condition.

In conventional MOT displays, object spacing might vary widely through the trial and object speed also sometimes varies. We designed a display in which spacing was relatively constant through the trial and speed did not vary at all. Reversals in direction were included to prevent participants from predicting the targets' final positions without tracking.

According to the theory of S. L. Franconeri et al. (2008), there should be no target number effect on the tracking speed limits. On the other hand, if tracking an object at higher speed requires more attentional resource, then the speed limit should be lower for tracking two than for tracking one, in both the large-spacing condition and the small-spacing condition.

## **2.2.1 Method**

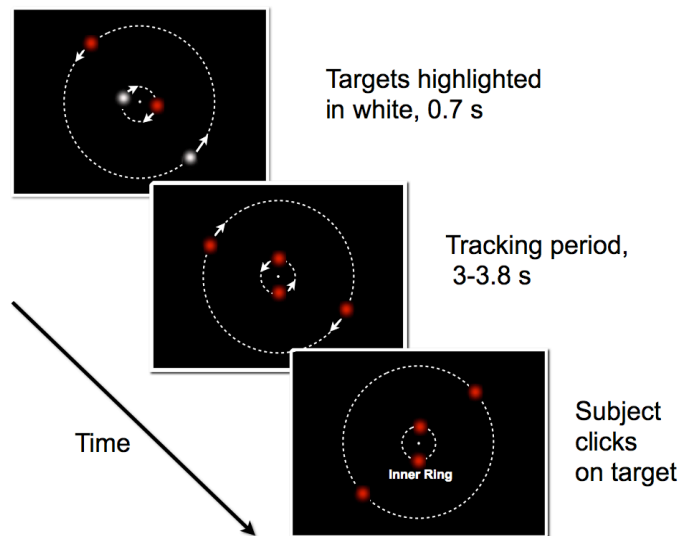
### **2.2.1.1 Participants**

Six participants (four male, two female, 29-38 years of age) who reported normal or corrected-to-normal vision agreed to participate, following approval of the protocol by the University of Sydney's ethics committee.

### **2.2.1.2 Stimuli**

Stimuli were displayed on a 21 in. SONY Multiscan G520 CRT monitor (1,024 x 768 resolution) with a refresh rate of 120 Hz controlled by a MacBook running a Python program that used PsychoPy software (Peirce, 2007). Viewing distance was 57cm in a dimly lit room, with a chin rest and forehead support to avoid subject head movement.

Four red Gaussian blobs (visible diameter  $1^\circ$ , luminance:  $12 \text{ cd/m}^2$ ) were presented on a black background ( $41^\circ \times 31^\circ$ , luminance:  $0.02 \text{ cd/m}^2$ ). A white fixation dot (luminance:  $167 \text{ cd/m}^2$ ) with a radius of  $0.1^\circ$  was presented at the centre of the display. Two circular trajectories were used, and a pair of blobs was placed in each trajectory (Figure 2.1). The trajectories were concentric; the inner circular trajectory had a radius of  $2^\circ$  in both separation conditions. In the large-separation condition the diameter of the outer trajectory was  $18^\circ$  and in the other condition, it was  $8^\circ$ . The blobs were always located in precisely opposite positions ( $180^\circ$  of the circle apart) in each circular trajectory.



**Figure 2.1.** *A schematic of the trial sequence for all experiments in Chapter 2*

After the targets are highlighted in white, all blobs become red and revolve about the fixation point. During this interval, the pair of blobs on each trajectory occasionally reverses movement direction, at random times independent of the other pair. After 3 to 3.8 s the blobs stop, one ring is indicated by presenting text next to it, and the participant clicks on one blob of that ring.

### 2.2.1.3 Procedure

Observers were told to maintain fixation on the white dot at the display centre. The trial started with one or two white target blobs. The remaining blobs were red distractor blobs. The blobs of the inner ring revolved in the opposite direction from that of the outer ring (set randomly on each trial). Their initial angle about the circular trajectory was set randomly on each trial. After a 0.7s target-cuing period, all blobs were again red (Fig 2.1). During the tracking period, the blobs occasionally reversed direction to prevent participants from predicting the final target positions from their initial positions and speeds. Each ring of blobs was independently assigned a series of reversal times, which succeeded each other at random intervals between 1.2 and 2 s. For this experiment's 3 to 3.8 s tracking interval, this resulted in 2 or 3 reversals.

In one condition, participants tracked two blobs and in the other, they tracked only one. In the one-target condition, only one blob was designated as a target: for half of trials, the target was in the outer ring and in the other half it was in the inner ring. In the two-target condition, one blob of each ring began white to designate them as targets.

At the end of the trial, in the one-target condition participants used the mouse to indicate which blob was the target. In the two-target condition, in half of trials participants were asked to indicate the target at the inner ring and in the other half of trials were at the outer ring.

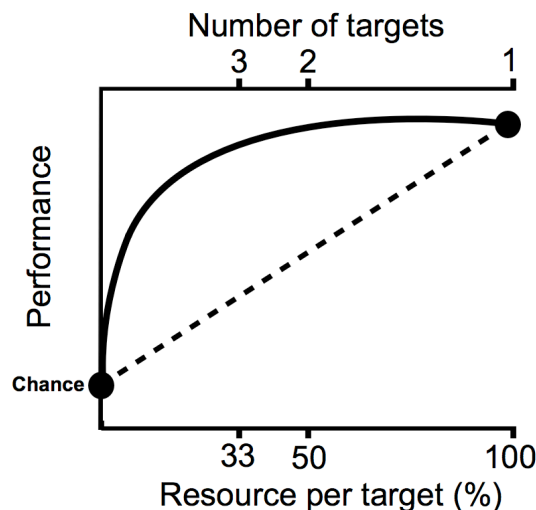
All objects revolved about fixation at the same rate. Five rotation rates (0.7, 1.0, 1.3, 1.6, and 1.9 revolutions per second, rps) were used on different trials, which were presented in pseudorandom order and fully crossed with the one-target versus two-target conditions. The eight hundred total experimental trials were divided into six sessions. Each participant did no more than two sessions a day and observers had a minimum break between sessions of 5 minutes.

#### **2.2.1.4 Data Analysis**

Plots of speed versus proportion correct were fit by a logistic regression that spanned from chance (50% accuracy) to a ceiling level of performance. The ceiling performance is determined by the lapse rate, which is the probability of an incorrect response that is independent of speed (Prins, 2012), such as hitting the wrong key or difficulty of the experimental condition. The larger lapse rate should be found more frequently in the difficult condition, than in the simple condition. For example, if spatial interference due to crowding were impairing tracking, it should occur more for conditions with higher target numbers and inflate the lapse rate. In Experiment 1, the lapse rate was varied to investigate whether spatial interference impairing tracking performance occurred at very slow speeds. In the fitting procedure of our data analysis, it was allowed to vary the lapse rate from 0 % to 10% to get the best estimate for each condition and each participant. This estimated lapse rate for each condition is reported in the results section. We refer to the speed at which performance is estimated by the regression to fall to 68% correct as the “speed limit”.

#### 2.2.1.4.1 The resource-versus-performance function

If tracking does require an attentional resource, how much resource is needed for successful tracking of a single target? The best way to answer this question is by quantifying the function that maps the proportion of the resource allocated to a target onto proportion correct. As described in Chapter 1, Norman and Bobrow (1975) proposed the resource-versus-performance function that relates the proportion of attentional resource devoted to a processing task to the likelihood of getting it correct. Here, we apply this function to investigate the relationship between performance and resource allocated to a single target (Figure 2.2).



**Figure 2.2. Hypothetical tracking resource-versus-performance functions**

The dashed line shows a linear function relating the proportion of the tracking resource (and the corresponding number of targets, top axis) to performance. This is a candidate function based on our results for fast speeds, but for slow speeds the function is believed to be more like the solid curve. The relatively flat right portion of the solid curve indicates that when attention is divided among a few targets, there is little cost for performance. Only when many targets are tracked (leftmost, steep part of the curve) do additional targets impose a significant cost for performance.

To ideally measure the resource-versus-performance function, a valid method is to ask observers on different trials to allocate different proportions of their attention to each of two targets - 90%: 10%, 80%: 20%, 70%: 30%, and so forth. Although this valid method may work for simple judgments regarding briefly presented stimuli (Bonnell & Miller, 1994; Lee, Koch, & Braun, 1999; Pastukhov et al., 2009), it would be difficult to induce observers to allocate a particular proportion of attention to two targets throughout a tracking trial.

Participants commonly report that they know when they fail to maintain their attention on a particular target for tracking. These reports are validated by the empirical success of the method of adjustment in tracking studies (Verstraten et al., 2000; Vul, Frank, Tenenbaum, & Alvarez, 2009), which requires that participants recognize when they succeed or fail to track the designated targets. Using this knowledge, during a trial, participants may shift the resource formerly used for a lost target to one of the other targets. It seems unlikely that, even if they are explicitly instructed to allocate (say) 30% of their resources to a target, that upon losing the other target the participant would leave 70% of their resources thereafter unused. In a further complication, toward the beginning of a trial, participants may recognize that the targets' speeds are too fast for all of them to be tracked, and then shift all of the attentional resource toward a subset of the targets. These possibilities of strategic allocation and reallocation (depending on the characteristics of targets) may make it difficult to enforce a particular allocation proportion.

To map the resource-versus-performance function for tracking objects, an alternative approach should be proposed. By the definition of resource theory, two data points on the function are already known, which are shown by two black solid circles in Figure 2.2. When tracking only one target, 100% of the resource is devoted to this target and performance is at maximum (the upper-right black circle). When no resource is available per target, performance should be at or very near chance (the lower-left black circle). The simplest possible resource-versus-performance function would then connect these two points with a straight line, which we refer to as the linear resource-versus-performance function (the dashed line in Figure 2.2). This linear function then predicts that when two targets are tracked (50% resource is allocated to each target), performance will be approximately halfway between the one-target level and chance performance.

In the literature on simple psychophysical judgments of briefly-presented stimuli, data supporting an approximately linear resource-versus-performance function was found for several concurrent discrimination tasks by Braun and colleagues (Lee et al., 1999; Pastukhov et al., 2009).

#### **2.2.1.4.2 The capacity-one benchmark**

The amount by which an increase in speed of a target may increase its resource demand is unknown. The extreme of possibility is that at high speeds, a target is so resource-demanding that additional targets cannot be tracked at all.

The capacity-one benchmark is proposed to interpret this possibility by calculating the performance level expected if participants can track only one target and completely ignore the second target. Calculating this will help to put any cost of splitting attention into perspective by comparing the cost to what would occur if participants could only track one target. In this scenario, where the observer is asked to track two targets, she can only manage to track one. Therefore, if asked at the end of the trial about the other target, she will perform at chance due to guessing. If asked about the target she tracked, her performance should be the same as if she were only asked to track one target.

For tracking two targets, the capacity-one benchmark yields the same performance level as the linear resource-versus-performance function described above section (shown as dashed line in Figure 2.2). Therefore, when the empirical performance for tracking two targets falls to this level (as we find for high target speeds), we cannot say whether it is because the linear function is correct or because participants only tracked a single target. It may be that at high speeds the resource requirement for successful tracking is even greater than that indicated by the linear function, and participants switch to tracking only one target as that yields better performance than attempting to track both.

Under the premise that a participant could track only one target (because it consumes all the attentional resource), we can calculate the expected proportion correct for the two-target condition with the performance of one-target condition. According to this, in half of the trials participants will track the target that is later queried, and in the other half of the trials they need to guess. The proportion correct for each speed is plugged into the equation ( $Y = 0.5 * 0.5 + 0.5 * X$ ; Y is the predicted curve and X is the psychometric curve of tracking one target.) to calculate the predicted performance in the two-target condition, on the assumption that only one target was successfully tracked. The mean and slope of the two-target predicted psychometric function were extracted from the psychometric curve of one-target tracking condition. Then, the corresponding predicted psychometric function was fit to the data.

For example, at slow speeds participants should get those trials correct, minus the lapse rate that is varied between 0% and 10% of the trials. The predicted proportion correct will be 74.75% (assuming the lapse rate is 1%) reflecting the 99.5% correct on trials in which they tracked the queried target and the 50% correct on the remaining half of trials. At very high speeds, they will perform at chance regardless of which target they attempt to track, yielding 50% correct. Thus, the span of the predicted psychometric curve for tracking two targets is from 50% correct performance to 74.75%.

The actual performance for most participants is well in excess of 74.75% at slow speeds in the two-target condition. This shows that at slow speeds, participants can simultaneously track more than one target. The solid curve in Figure 2.2 supports this. At slow speeds tracking is very accurate regardless of whether 50% or 100% of the resource is used. If increased speed is associated with more consumption of attentional resource, at faster speeds capacity may eventually be restricted to a single target and the capacity-one benchmark will closely resemble performance. Unfortunately, detailed comparison of observed with theoretical psychometric functions requires thousands of trials in each observer



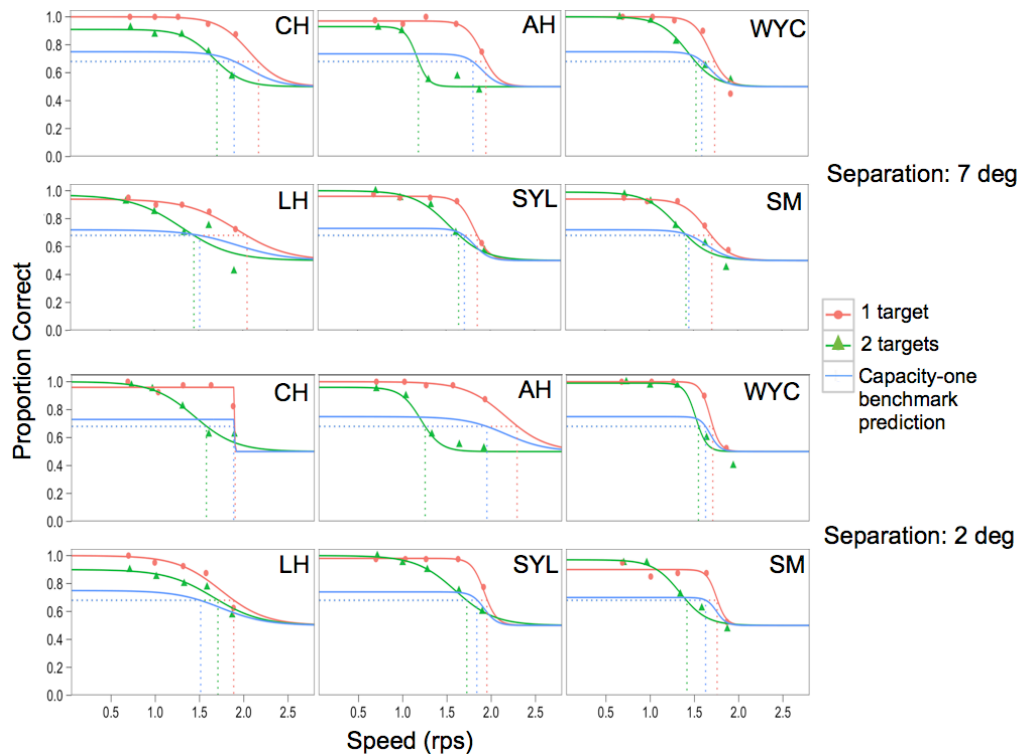
and is fraught with difficulties (Zychaluk & Foster, 2009). Nonetheless, in this more limited study the speed limits (68% thresholds) predicted under the extreme scenario of only one target tracked still provides a useful benchmark against which to compare the size of any observed drop in speed limit in the two-target condition.

### **2.2.2 Results**

The data and associated psychometric plots for each of the six participants in both conditions of Experiment 1 are shown in Figure 2.3. For every participant, the speed limit (68% threshold) for tracking one target is better than for tracking two targets.

Recall that the capacity-one benchmark predicted data begins with the assumption that participants can track only one target, with performance as a function of speed taken from the one-target condition. However, because the assumption is that participants can only track one target, even at slow speeds they must guess in the half of trials for which they track the non-queried object. At low speeds, the accuracy predicted by the capacity-one benchmark is substantially lower than the actual performance of every participant. Indeed at very low speeds participant performance is near 100% correct. If participants could only track one target, performance should never exceed 75% correct for two targets. This suggests that participants can track more than one target when they move slowly (as has been found by many studies before). At high speeds, however, actual performance is closer to the benchmark and in some cases even drops below the benchmark. Actual performance below the benchmark performance can occur if observers try to track both targets but can actually only track one target. Splitting their attentional resource between two targets does not yield enough resource to successfully track either, so performance is below that expected if one is tracked. Nonetheless, the speed limits (68% thresholds) predicted under the extreme scenario of only one object tracked still provides a useful benchmark against which to compare the

size of any observed drop in speed limit in the two-object condition. Therefore, we will still use this benchmark to assess the resource costs in Experiment 1.

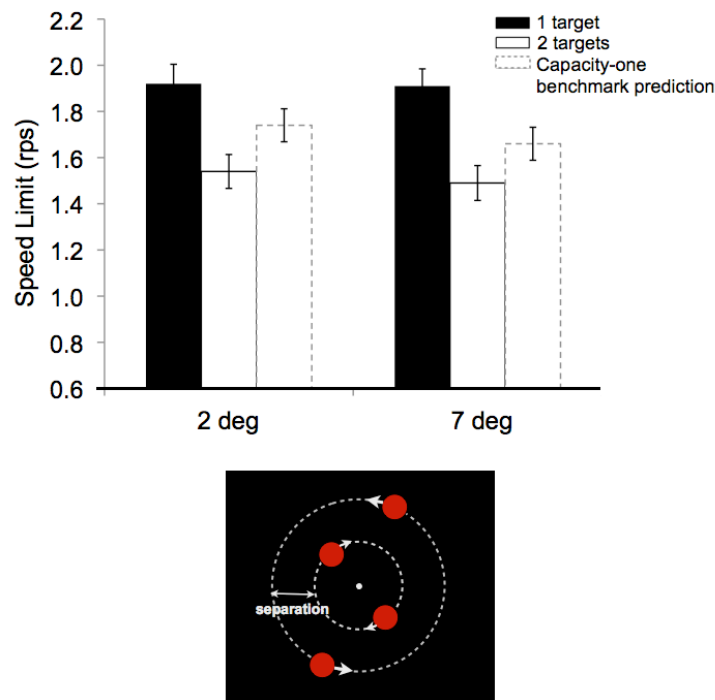


**Figure 2.3. Individuals' performance in Experiment 1**

For each participant in Experiment 1, proportion correct is shown for each speed, in the one-target (red curve) and two-target (green curve) conditions. Also shown is the prediction for the two-target condition (blue curve) if the participant had a capacity limit of one target. Dotted lines show the 68% thresholds.

The speed limits, averaged across participants, are shown for each condition in Figure 2.4. The averaged speed limit for tracking one target (1.92 rps) was higher than for tracking two targets (1.51 rps) by a large margin—0.41 rps,  $F(1, 5) = 14.403$ ,  $p = 0.013$ , partial  $\eta^2 = 0.742$ . This difference was statistically significant according to planned paired t-tests across participants, for both the small separation ( $t(5) = 2.797$ ,  $p = 0.038$ , Cohen's  $d = 1.959$ ) and large separation ( $t(5) = 4.595$ ,  $p = 0.006$ , Cohen's  $d = 2.314$ ) conditions. No statistically significant interaction of separation and number of targets was present, according to a 2 (number of targets: one or two)  $\times$  2 (separation: small or large) ANOVA ( $F(1, 5) = 0.237$ ,  $p = 0.647$ , partial  $\eta^2 = 0.045$ ).

Numerically, the two-target speed limit (1.51 rps) was slightly lower than that predicted by the capacity-one benchmark (1.70 rps), yet this was not statistically significant for the small separation ( $t(5) = -1.681, p = 0.154$ , Cohen's  $d = -1.145$ ) or for the large separation ( $t(5) = -1.888, p = 0.118$ , Cohen's  $d = -0.963$ ) conditions.



**Figure 2.4. Averaged speed limits in Experiment 1**

**Bottom panel.** The stimulus arrangement in Experiment 1. **Top panel.** The mean speed limits (68% thresholds),  $n = 6$ . The speed limit for tracking two targets is substantially worse than the speed limit for tracking one, and is similar to that predicted by the capacity-one benchmark (dashed bars). Error bars show one standard error across 6 participants.

The speed limit in the large separation conditions was negligibly and non-significantly lower than in the small separation conditions, both for one target (0.01 rps lower, paired t-test,  $t(5) = 0.031, p = 0.977$ , Cohen's  $d = 0.015$ ) and two targets (0.05 rps lower, paired t-test,  $t(5) = 0.936, p = 0.392$ , Cohen's  $d = 0.268$ ).

As described in the *Data Analysis* part, we are concerned that parts of the difference in speed limits between the one-target and two-target conditions might be caused by greater spatial interference between targets in the two-target condition. If spatial interference impairs the tracking performance in more trials in the two-target condition, the psychometric function

would saturate at a lower ceiling than the one-target condition. The ceiling level of performance is usually captured by the lapse rate, which is the probability of an incorrect response that is independent of speed. To assess the possibility of spatial interference, in the psychometric fitting procedure, the lapse rate is allowed to vary from 0% to 10%, so that it is estimated for each subject and condition. The lapse rate should be lower in the two-target condition than in the one-target condition if spatial interference is the main detrimental effect on tracking.

No evidence was found for a higher lapse rate in the two-object condition (0.03) than in the one-target condition (0.03). In addition, there was no significant difference for the lapse rates between in the small separation (0.03) and large separation condition (0.03). Statistically, a repeated-measures ANOVA was conducted with separation and target number as the independent variables and lapse rates as the dependent variable. There was neither a significant target number ( $F(1, 5) = 0.043, p = 0.844, \text{partial } \eta^2 = 0.008$ ) or separation effect ( $F(1, 5) = 0.019, p = 0.895, \text{partial } \eta^2 = 0.004$ ) on lapse rates, nor a significant interaction between two factors,  $F(1, 5) = 0.019, p = 0.895, \text{partial } \eta^2 = 0.004$ .

### **2.2.3 Discussion**

Previous literature already documented an effect of speed on number of targets that can be tracked (Bettencourt & Somers, 2009; Liu et al., 2005). However, Franconeri et al. (2008) suggested that the detrimental effects of speed on number of objects that can be tracked might be explained by interference associated with the increase in instances of small separation between objects at higher speeds. That is, a greater number of putative interactions between object representations at high speeds may have resulted in the decreased tracking capacity in previous studies. However, here we found a substantial effect of number of targets on speed limit, even for objects presented at spacing so large that any interactions are unlikely.

The capacity-one benchmark puts the differences of speed limits in perspective, by giving the speed limit that would have occurred had participants simply ignored one of the targets in the two-target condition. Remarkably, the speed limit in the two-target condition was not better than this prediction (see Figure 2.4). This makes it clear that the effect of target number on speed limit is very large indeed.

There was some evidence (not statistically significant) that performance fell below the capacity-one benchmark. For tracking two targets, the capacity-one benchmark makes the same predicted performance as a linear resource-versus-performance function. What would occur if participants gave up on one target and focused all resource on the other target is equivalent to that 50% of the resource was not enough to track each of two fast-moving targets. The statistically non-significant finding of that performance falls below the capacity-one benchmark suggests that the true resource-versus-performance function falls below the linear function. In other words, for fast targets splitting the resource in two may yield performance worse than halfway towards chance from the one-target level. For example, more than half the resource may be required to have any tracking success with fast targets and therefore if the participants try to track both targets, they will fail and have to guess regarding both, yielding performance even worse than the capacity-one benchmark.

It might seem that the Franconeri theory could be salvaged by positing that the objects interacted in the large-separation condition, even though this is somewhat implausible given how far they were from each other's crowding zones. However, on this account the Franconeri hypothesis still predicts that the interference should have been substantially greater in the small-spacing condition. Even still, we found no significant effect of separation on performance.

Perhaps the 7 deg separation in Experiment 1 may not have been large enough to avoid spatial interference and not different enough from the smaller separation to yield a

smaller amount of interference. We conducted a simple additional experiment (Experiment 1b) with an even larger separation, with 2.5 deg for the inner ring and 13 deg for the outer ring. In pilot testing, we noticed that the speed limit for the outer ring was substantially slower than that of the inner ring, when considered in terms of revolutions per second (this may be related to the jump size between successive frames being larger at the higher separation, owing to the greater linear speed at high eccentricity for a particular number of revolutions per second, together with the limited, 160 Hz refresh rate). To address this in the design of Experiment 1b, the blobs in the outer trajectory moved 0.4 rps more slowly than those in the inner. Whereas in Experiment 1 each of two circular trajectories contained two blobs, in Experiment 1b each contained three blobs (lowering the guessing rate to 33%). Except for those changes, the apparatus and stimuli used were identical to those used in Experiment 1. Four observers (3 male, aged 29-37) participated in at least 160 trials each at speeds of 0.9, 1.2, 1.5, 1.9, and 2.2 rps (according to inner ring). The averaged speed limit for tracking one target (1.73 rps) was significantly higher than that for tracking two targets (1.34 rps) according to a paired t-test ( $t(3) = 3.883, p = 0.03$ , Cohen's  $d = 2.048$ ). This disconfirms the spatial interference theory for why the speed limit was lower for two targets in the original experiment. Using the very large separation, it was implausible that there was spatial interference between two targets. Yet the cost on speed limits from additional targets nevertheless occurred. This is compatible with diminishing the amount of resource available per target, rather than because of spatial interference among targets.

Although it appears the Franconeri theory cannot explain these results, one element of the theory remains unaddressed. According to Franconeri et al. (2010), the primary reason that tracking performance decreases with object speed is because the object travels farther in the allotted time for the trial, which results in more instances in which the objects come relatively close to each other and interfere. This concern might have some effects on the

results in Experiments 1 and 1b because the distance that objects travel is longer at high speeds than at slow speeds. To test whether this contributed much to the effect of object speed, in Experiment 2 we equated cumulative distance travelled across speeds by appropriately adjusting the durations of the trials.

### **2.3 Experiment 2: Constant Travelled Distance, Bilateral Arrangement**

From the results of Experiment 1 and Experiment 1b, speed limits decrease substantially when the number of tracked targets increases from one to two. This supports the flexible-resource theory's assertion that when observers need to track two moving targets simultaneously, each target is allocated only half of the total attentional resource. Franconeri et al. (2010) however provided evidence to support the notion that the critical factor limiting tracking performance is the number of times that objects pass too closely to each other (inter-object spatial interference) rather than the object speed. The cumulative distances that objects travel as a manipulation factor was used in their study to represent the occurrence probability of inter-object spatial interference. The further the cumulative distances, the more frequently the putative occurrence of inter-object spatial interference applied. The results showed that tracking accuracy significantly dropped with increasing cumulative distance.

The concern of Franconeri et al. (2010) might explain the large target number effect on speed limits in Experiments 1 and 1b by suggesting that there were more occasions for spatial interaction when the stimulus was presented at high speeds. In the high-speed trials, the targets went about the circular trajectory many more times and thus came relatively close to the other target more times. As spatial interference has been suggested to occur mostly among targets (Franconeri et al., 2010; Franconeri et al., 2008), in the two-target condition there would be more interference. If distance travelled had been equated across speeds, the additional interference in the two-target condition would be equal across speeds. But because distance travelled was greater at high speeds, the interference should be particularly large at

high speeds, potentially explaining the large speed-limit cost. Note that spatial interference could only occur if it extended much larger distances than found in the crowding literature (Pelli & Tillman, 2008), so it is unlikely that any interference occurred. However we nevertheless decided to assess the possibility.

If we equate distance travelled, the putative spatial interference should not be higher at faster speeds. According to the spatial interference theory, then, the two-target speed limit cost associated with additional targets should be much reduced or disappear. In Experiment 2, the relationship between speed limit and the number of tracked objects is investigated with equal cumulative travel distances.

Franconeri's spatial interference theory predicts that if the occurrence probability of inter-object spatial interference influences the accuracy for tracking multiple objects, when we test participants' performance across speeds with constant travel distance, tracking accuracy should be equal at slow or intermediate speeds. At very high speeds, a substantial drop on tracking performance, (which they explained results from the data limitation), comes from weak visual inputs. We instead found that tracking accuracy decreased with higher object speeds. Therefore, we conclude that speed itself does affect tracking performance.

### **2.3.1 Method**

#### **2.3.1.1 Participants**

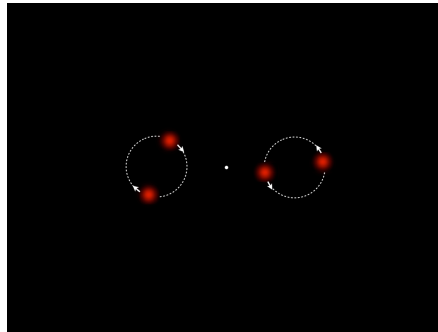
The six participants (four male, two female, 29-36 years of age) also participated in Experiment 1.

#### **2.3.1.2 Stimuli**

The apparatus and stimuli used were the same in Experiment 1 except for the few changes described here. This experiment modified the arrangement of stimuli in order to satisfy two goals: (1). Two used circular trajectories need to maintain the same speed throughout one trial. (2). Cumulative travel distances of objects were equal for each trial. In



this experiment, two red Gaussian blobs were paired and always  $180^\circ$  apart on each of two imaginary rings. The two imaginary rings were horizontally aligned with one in the left visual field and one in the right visual field, centred at a distance of  $3^\circ$  from the fixation point (Figure 2.5). The blobs orbited along their imaginary centre point on each ring, all with the same speed.



**Figure 2.5. Display of Experiment 2**

Two red Gaussian blobs constituted one virtual ring and two rings were horizontally aligned with one in the left visual field and one in the right visual field, centred at a distance of  $3^\circ$  from the fixation point

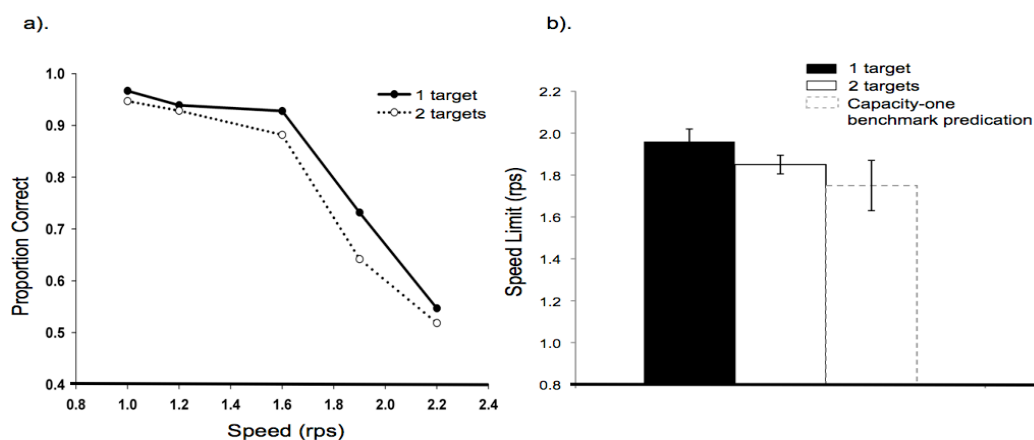
### **2.3.1.3 Procedure**

The sequence of events on a given trial was identical to that in Experiment 1 except for the few changes described here. In Experiment 1, the tracking duration was randomly set to between 3 and 3.8 seconds whereas in Experiment 2, the tracking duration was varied with speeds across trials, to achieve a constant distance travelled of 6.6 revolutions. The cumulative distance was made constant by using shorter tracking intervals for higher speeds. Five rotation rates (1.0, 1.2, 1.6, 1.9, and 2.2 rps) and 5 corresponding tracking periods (6.6, 5.5, 4.125, 3.47, 3 seconds) were used. Each observer participated in 120 trials at each of the five rates, yielding 600 experimental trials in total, divided into five sessions. Each participant did no more than two sessions a day and observers had a minimum break between sessions of 5 minutes.

### 2.3.2 Results

Mean tracking accuracy for tracking one and tracking two targets for the five test speeds is shown in Figure 2.6a. Under the condition of equal travel distances, this data demonstrated that a large reduction in tracking accuracy occurs with increasing the object moving speeds. Tracking performance dropped steeply when the speed was over 1.6 rps. A 2 x 5 repeated measures ANOVA revealed a significant main effect of speeds,  $F(4, 20) = 46.399, p < 0.001$ , partial  $\eta^2 = 0.903$ . There was little to no effect of number of tracked targets,  $F(1, 5) = 2.428, p = 0.18$ , partial  $\eta^2 = 0.327$ , and no interaction between two factors,  $F(4, 20) = 1.348, p = 0.287$ , partial  $\eta^2 = 0.212$ . According to Figure 2.6a, a significant drop in tracking accuracy is found between 1.6 and 1.9 rps with the post-hoc analysis ( $p = 0.044$ ).

The speed limit is estimated as the speed corresponding to 68% correct with psychometric curve (see details in Experiment 1), and is plotted in Figure 2.6b. The speed limit for tracking one target (1.96 rps) was slightly higher than tracking two targets (1.85 rps), but this was not significant, Paired t-test,  $t(5) = 1.355, p = 0.233$ , Cohen's  $d = 0.899$ . Additionally, non-significant difference was found in speed limits between tracking two targets and that predicted by the capacity-one benchmark (1.75 rps), Paired t-test,  $t(5) = 0.728, p = 0.5$ , Cohen's  $d = 0.455$ .



**Figure 2.6. Results of Experiment 2**

(a). Mean tracking proportion correct with five different speeds when observers tracked one and two targets. (b). Speed limits for tracking one and two targets, and the two-target predicted speed limit by the capacity-one benchmark.

### 2.3.3 Discussion

The findings of this experiment were contrary to Franconeri et al. (2010)'s suggestion that the critical factor limiting tracking performance is the cumulative distance that objects travel. A main effect of speed on tracking accuracy was found in this experiment even though it controlled the cumulative distance of objects that travelled. In the experiment of Franconeri et al. (2010), they varied speed and trial duration across trials and found tracking accuracy declined as the product of speed and trial duration increased. But in our Experiment 2, we equate cumulative distance that objects travel by using shorter trial duration for higher speeds. Thus, tracking performance declined with increasing speed in Experiment 2 cannot be explained by the notion of Franconeri et al. (2010) that increased number of close encounters among targets at higher speeds. The finding in Experiment 2 is instead consistent with the flexible resource theory that fast-moving targets require more attentional resource. There was no significant target number effect on speed limit, only a non-significant trend for the maximum tracking speed of tracking one target to be higher than for tracking two targets.

Why was there a large effect of number of objects tracked on speed limits in Experiments 1 and 1b, but less or no effect in Experiment 2? The discrepancy may be caused by the possible hemifield specificity of the attentive tracking resource. Alvarez and Cavanagh (2005) proposed that there are two independent resource pools within left and right hemispheres for attentive tracking. This theory could explain the conflict in findings between Experiments 1 and 2. In Experiment 2, the two imaginary rings of stimuli were arranged independently within right and left visual hemifields. Independent hemisphere-specific resources would provide each target with an independent resource. As a result, the speed limit for tracking one object would not be affected by whether a target was tracked in the opposite hemifield. By contrast, in Experiment 1 the two imaginary rings were presented centrally and spanned two hemifields. In order to successfully track targets in Experiment 1,

the two hypothesized independent hemisphere-specific resources would have to collaborate. In the two-target condition, each target should have been allocated just half of all the resource (left + right hemisphere-specific resources). Thus, based on the flexible-resource theory of attention, the speed limit of tracking one target should be significantly higher than that of tracking two targets. In Experiments 4 of Chapter 3, we will explore whether two independent hemisphere-specific resources influence the tracking speed limit by modifying the experiment of Alvarez and Cavanagh (2005)'s study.

### **2.4 Experiment 3: Equal-Distance Experiment with Eye Tracker Monitoring**

Franconeri et al. (2010) plotted performance in terms of cumulative travel distance as well as speed, and observed that the cumulative travel distance was more strongly correlated with performance than was speed. They suggested that it occurred because larger cumulative distance resulted in more inter-object interactions, which they propose to be the primary determinant of tracking performance. According to this element of their theory, there should be little or no effect of speed if cumulative distances are equated across speeds (except for data limitation at very high speeds). From Experiment 2, we confirmed the effect of speed on tracking accuracy for a condition where the cumulative distance travelled by the objects was constant, but the target number effect on speed limits was not found. The hemisphere-specific resource theory could explain the non-significant cost with additional targets. In Experiment 3, the two circular trajectories were concentrically aligned on the fixation point to involve both hemisphere-specific resources, similar to in Experiment 1.

Although previous work found that eye movements do not affect tracking performance much (Fehd & Seiffert, 2008; Scholl & Pylyshyn, 1999; Scholl et al., 2001), enforcing central eye fixation may be more critical in our paradigm. Our main result is a much poorer speed limit for tracking two targets than for tracking one, and attributing the effect to attention assumes that participants did not track one target with their eyes, using

attention only for the second target. All participants used in this experiment had extensive experience fixating in other experiments, but to eliminate any doubts, here we monitored eye movements with an eye tracker.

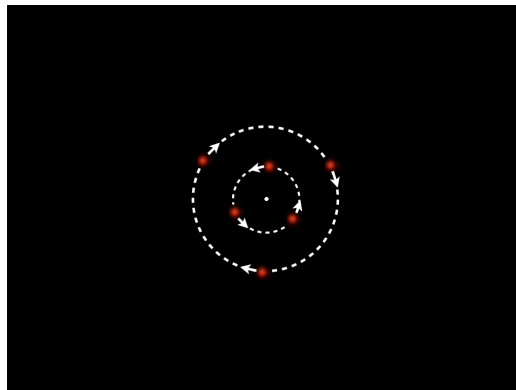
## 2.4.1 Method

### 2.4.1.1 Participants

Six participants (four male, two female, 29-37 years of age) were used in Experiment 3 and five of these participants had also previously participated in Experiment 1.

### 2.4.1.2 Stimuli

The apparatus and stimuli used were identical to those in Experiment 1 except for the few changes described here. In Experiment 1, each of the two circular trajectories was composed of two Gaussian blobs. In Experiment 3, each of the two circular trajectories consisted of three blobs (which lowered the guessing rate to 33%), equally spaced about the trajectory (Figure 2.7). The inner circular trajectory had a radius of 2.5 deg and the radius of the outer circular trajectory was 5.5 deg.



**Figure 2.7. Display of Experiment 3**

The objects travelled in two concentric circular trajectories that were centred on the fixation point and three red Gaussian blobs constituted one virtual rings. Each blob of the triplet was presented apart  $120^\circ$  from others. The inner ring had a radius of 2.5 deg and the radius of the outer ring was 5.5 deg.

### 2.4.1.3 Procedure

The sequence of events on a given trial was identical to that of Experiment 2 except the few changes described here. In Experiment 2, the cumulative distance that objects travel

was 6.6 revolutions on every trail. But in Experiment 3, the cumulative travel distance was shortened from 6.6 to 3.6 revolutions. Monitoring eye movements elongates the duration of testing session. The reason we shorten the cumulative travel distance for each trial is to avoid observers losing their patience to do this task owing to longer testing session. Five rotation rates (0.6, 0.9, 1.2, 1.5, and 1.8 rps) were used, which to achieve a constant distance travelled of 3.6 revolutions, yielded 5 corresponding tracking durations (6, 4, 3, 2.4, 2 seconds). Each observer participated in 48 trials for each of the five rates, yielding 240 experimental trials in total, divided into two sessions run on different days.

#### **2.4.1.4 Eye Tracking**

Eye movements were monitored using an EyeLink 1000 eye tracker (SR Research, 2010). At the beginning, the eye-tracking system was calibrated and validated using the standard five-point calibration. The experimenter monitored the video image of the participant's eye at the beginning of each trial, to ensure that the participant fixated and that the eye-tracker continued to report this correctly. The eye tracker was recalibrated if, during the interval before the trial, it registered the participant's eye location as being away from fixation, even though the participant reported fixating. If the participant moved his or her eye by more than 1.5 deg from the fixation point, the trial was discarded.

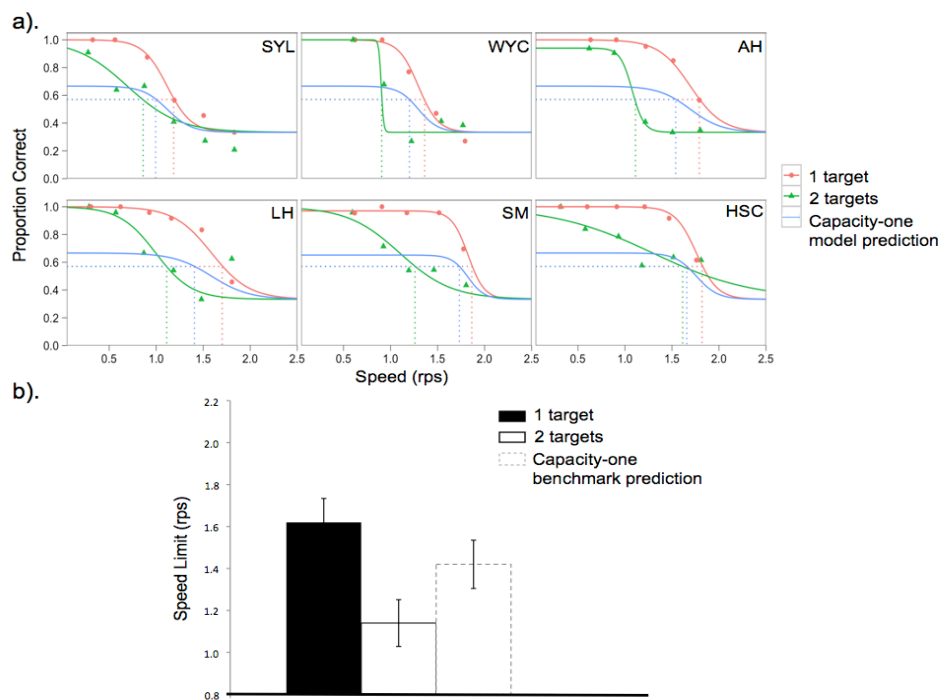
#### **2.4.1.5 Data Analysis**

The curves were fit as in Experiment 1, adjusted for the lower 33% chance rate of the present experiment. The prediction from the capacity-one benchmark was also adjusted accordingly, spanning 33% correct performance to 66.25%. The threshold accuracy considered the speed limit was set to 57% to achieve the comparable point on the psychometric curve as the 68% point in Experiment 1.

## 2.4.2 Results

The criterion of eye movement greater than 1.5 deg from fixation led to the exclusion of 8.8% of the trials (SD = 3.5% across participants). The eye-tracker was less reliable for the three participants who wore glasses, and not including them, only 3.2% of trials were excluded. A repeated-measures ANOVA revealed no significant effect of speed ( $F(1, 5) = 1.11$ ,  $p = 0.379$ , partial  $\eta^2 = 0.182$ ) or target number ( $F(1, 5) = 2.373$ ,  $p = 0.184$ , partial  $\eta^2 = 0.322$ ) on eye movements greater than 1.5 deg.

The effect of speed on proportion correct is plotted in Figure 2.8a, for tracking one and tracking two targets. For every participant, the speed limit (57% threshold) for tracking one target is better than for tracking two targets.



**Figure 2.8. Results of Experiment 3**

(a). Proportion correct is shown for each speed in the one-target (red curve) and two-target conditions (green curve) of Experiment 3 for each participant. Blue curve is the prediction for the two-target condition if the participant had a capacity limit of one target. Dotted lines show the 57% thresholds. (b). Speed limits for tracking one and two targets and the two-target predicted speed limit as the equal cumulative travel distances. Error bars show one standard error across 6 participants.

The mean thresholds in each condition are plotted in Figure 2.8b. The average speed limit for tracking one target (1.62 rps) was substantially higher than tracking two targets

(1.14 rps), paired t-test,  $t(5) = 6.402$ ,  $p = 0.001$ , Cohen's  $d = 1.727$ . In addition, the two-target speed limit predicted by the capacity-one benchmark was significantly higher than that for the empirical two-target speed limit, paired t-test,  $t(5) = -4.12$ ,  $p = 0.009$ , Cohen's  $d = -1.001$ . This indicates that at high speeds observers only have enough resource to track one target, but continue to divide their resources among the two so that they fail to track both.

### **2.4.3 Discussion**

The finding of this experiment was contrary to the suggestion of Franconeri et al. (2010) that the critical factor limiting tracking performance is the cumulative distance that objects travel. Varying speeds over a range similar to that was critical in Experiment 1 caused performance to drop from very accurate to near chance, even though there were no differences in cumulative distance that objects travel. This is similar to what was found in Experiment 2. With the targets both travelling among both hemifields rather than being confined to a hemifield as in Experiment 2, a large target number effect on speed limits was found.

Strong evidence of two independent hemisphere-specific resources for attentive tracking was reported by Alvarez and Cavanagh (2005). However, they did not vary object speed, but rather number of objects to track. Their finding is described well by their paper's abstract: "twice as many targets can be successfully tracked when they are divided between the left and right hemifields as when they are all presented within the same hemifield". To explain this finding, they proposed that the tracking resources are hemisphere-specific.

If availability of this hemisphere-specific resource also determines the maximum speed at which objects can be tracked, this could explain our finding of little or no decrement on speed limit when tracking two targets presented to different hemispheres (Experiment 2). To test this theory, we performed some experiments in which we directly compared



performance for a display with targets presented to opposite hemispheres to a display with targets presented to the same hemisphere. These experiments are discussed in Chapter 3.

## **2.5 Discussion of Experiments 1-3**

The large cost of a second target on speed limit provides good evidence for the resource theory of tracking. Both speed and target numbers deplete the tracking resource, so that at high speeds, fewer targets can be tracked. Indeed, the demand of high speeds is so large that performance is similar to that expected if only one target could be tracked.

The findings of the current experiments are consistent with the claim across multiple studies that the tracking limit depends on the task demands and requirements of tracking each target (Alvarez & Franconeri, 2007). Alvarez and Franconeri (2007) measured the maximum speed from 1 target to 8 targets by participants self-adjusting the object moving speed with arrow keys (left arrow to decrease and right arrow to increase speed) until they can accurately track all targets for around 5s. Experiment 1 showed that the speed limit decreased by 22% from tracking one object to tracking two objects, and this result is comparable to the 30% found in the classical MOT task in the study of the Alvarez and Franconeri (2007). The larger decrease in the Alvarez and Franconeri (2007) study may reflect the spatial interference present in their display when objects passed very close to each other. The progressive decrease in speed limit with increase in the number of tracked targets agrees with the flexible-resource theory of attention. In Experiment 1, the speed limit is found to be up to 1.92 rps when all attentional resources are allocated to one target. When available resources are divided between two targets, the speed limit is reduced to 1.51 rps because the amount of resource for each target is reduced. In the equal cumulative travel distances condition in Experiment 3, the target number effect on speed limit is also found and the average speed limit for tracking one (1.62 rps) target is significantly higher than tracking two (1.14 rps) targets.

### **2.5.1 Spatial Interference is Not the Main Reason For Decrease of Speed Limits**

It would be difficult to reconcile these results with the FINST and spatial interference theories. According to the FINST theory (Pylyshyn & Storm, 1988), the speed limit for tracking should not be affected by changing the tracking load from one to two targets. However, most experiments in this chapter were inconsistent with this theory, as shown by the repeated finding that the speed limit for tracking one target was significantly higher than that for tracking two targets. The only exception was when the targets were in different hemifields (left and right) where they may be tracked by different hemisphere-specific resources.

According to spatial interference theory (Franconeri et al., 2010; Franconeri et al., 2008), the speed limit for tracking can only be affected by the number of targets if the objects are sufficiently close to cause interference among their attentional spotlights. To avoid spatial interference, we used wide separation between targets in Experiment 1. In the large-separation condition the two targets never came closer than 7 deg, much larger than the approximately half-eccentricity crowding zones of approximately 4.5 deg for the outer blob and 1 deg for the inner blob, predicted by extensive psychophysical work (Bouma, 1970; Pelli & Tillman, 2008). The distracter blob for each target was on the opposite side of the fovea, very far in cortical distance, and should not have caused any interference (Pelli, 2008).

Could spatial interference theory be salvaged with the proposition that the interference zones of the attentional spotlights are extraordinarily large? Not likely, because the interference still ought to increase with proximity (Shim et al., 2008), yet the speed limit cost of an additional target was very similar at a much smaller separation.

The present findings challenge the hypothesis that humans can track unlimited number of targets at a given speed under conditions of no crowding (Franconeri et al., 2010; Franconeri et al., 2008). Franconeri et al. (2008) suggest that the limit on the number of

tracked objects comes from inter-object spatial interference rather than object speed. Their suggestion is that increasing speed will increase the number of close encounters between targets and distractors per unit time. However, in Experiment 1, we showed even with large separation that the speed limit significantly decreased from 1.92 rps of tracking one target to 1.51 rps of tracking two targets. We further extended this result with the extraordinarily large separation (10.5 deg) in Experiment 1b, and still found the large cost of an additional target on the speed limit.

Contrary to our finding, negligible target number effect was found by Shim et al. (2008) when comparing tracking one target and tracking two targets at large separations. However, the speeds they chose were not fast enough to investigate the target number effect on speed limits. According to our Experiment 1, the difference in tracking performance between one and two targets emerged as the speed increased above 1 rps (12 deg/s). Therefore, if Shim et al. (2008) tested their participants at higher speeds than 11 deg/s, a significant target number effect might have been found owing to a higher demand on attentional resource when tracking two targets.

Previous literature documented that tracking accuracy was worse at closer proximity when tracking two targets (Shim et al., 2008; Tombu & Seiffert, 2008) but little evidence was previously available regarding the relationship between proximity and speed limit. Only Carlson et al. (2007) showed that the speed threshold was higher for more widely separated targets. In contrast, our Experiment 1 provided evidence that the inter-object separation factor was independent of the number of tracked objects, and there was no significant difference on speed limits between two distinct separations (large or small spacing conditions). The distinction from our Experiment 1 is that for the small spacing condition in the study of Carlson et al. (2007), the target was presented within the crowding zone of the other targets (Bouma, 1970), where a target is separated from the other target by less than half the target's

eccentricity. In contrast, for our Experiment 1, proximities of two conditions were both outside crowding zone of each other.

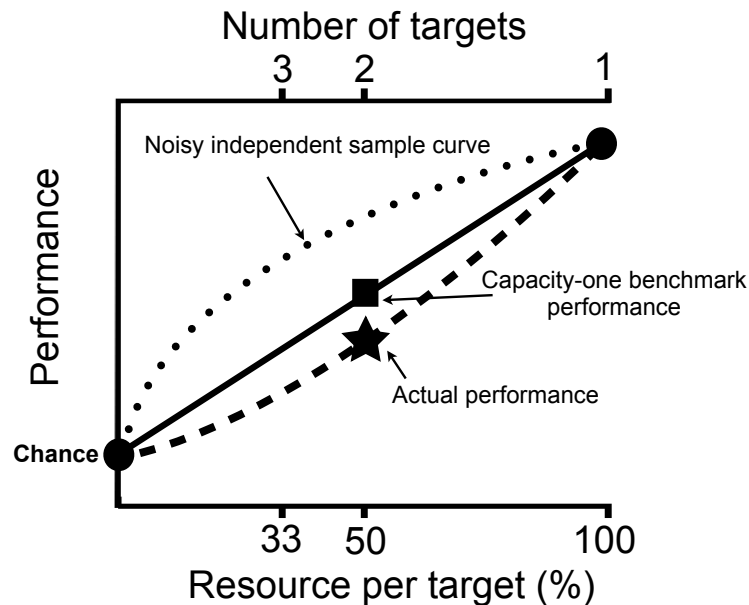
Using the desirable paradigm that independently manipulated the influential factors, resource allocation for object tracking can only be influenced by speed change when ruling out the possible confounds. Consistent with our finding, Tombu and Seiffert (2011) also demonstrated a substantial speed effect on tracking performance independent of proximity. They studied independently the speed effect and proximity effect in multiple object tracking with what they called planets and moons tracking, which resembles our paradigm in that it allowed better control of inter-object proximity and speed than the traditional MOT task. Unlike our Experiment 1, the three proximity conditions they used were all located within the crowding zone. Our finding of Experiment 1 adds that resource allocation resulted in reduced speed limits with stimuli presented outside the crowding zone.

### **2.5.2 Resource Costs Are Described by the Capacity-One Benchmark**

The capacity-one benchmark proposed by the present chapter provides a new perspective on the effect of additional targets by allowing them to be compared to what would have occurred had if participants track only one target and completely ignore the other. The capacity-one benchmark assumes that at high speeds, a target is so resource-demanding that additional targets cannot be tracked at all. When tracking two targets, participants only manage to track one and must guess regarding the other target at the end of trial.

The performance level for tracking two targets predicted by the capacity-one benchmark is shown with the black square in Figure 2.9, which is identical to the performance predicted by 50% of resource parallel allocation between two targets with a linear resource-versus-performance function (as shown with black line). Most experiments in this chapter show that at the fastest speeds, empirical performance (a star in Figure 2.9) drops below the benchmark performance (a square in Figure 2.9). It indicates that at high speeds the

resource requirement per target for successful tracking two targets is even greater than that indicated by the linear function, or participants switch to tracking only one target as that yields better performance than attempting to track both.



**Figure 2.9. Resource-versus-performance functions at high speeds**

The dotted line shows a prediction based on a noisy independent-samples idea, so that performance increases with the square root of the resource applied. Because at fast speeds we have found that for tracking two targets, performance falls at or below the capacity-one benchmark in most experiments of this chapter, the resource required for successful tracking is higher even than is shown by the linear resource-versus-performance function. The shape of the function is unknown, but one possibility is shown by the dashed curve.

A different resource function for tracking was proposed by Horowitz and Cohen (2010). Horowitz and Cohen (2010) assessed participants' ability to report, after the display had stopped, the final direction that tracked targets had been moving. They found evidence that performance matched the resource function predicted from a noisy independent samples model of the resource. Specifically, the theory is that resource improves performance by improving the precision of tracking in the same way that increasing the number ( $n$ ) of noisy samples taken from a distribution improves the precision (standard deviation) of the estimate of the mean. Specifically, the standard deviation improves with the square root of  $n$ . Note that the dependent variable in the Horowitz and Cohen (2010) experiment was not tracking performance but rather the standard deviation of the reports of targets' final motion direction.

The relationship between precision and proportion correct in tracking targets is uncertain. If this relationship is linear, the noisy independent-samples theory predicts that proportion correct will increase with the square root of  $n$ , as schematized in Figure 2.9. The corresponding curve (dotted curve) in the graph is simply that for which performance grows in proportion to the square root of resource, with the additional constraints that zero resource yields chance performance and 100% resource yields the one-target performance. However, our findings in this chapter (star in Figure 2.9) are contrary to the noisy independent-samples theory (a dotted curve in Figure 2.9).

### **2.5.3 Tracking Resource might be Hemisphere-Specific**

Alvarez and Cavanagh (2005) proposed that there are two independent hemisphere-specific resource pools in the right and left cerebral hemispheres and each target is tracked by one single attentional resource in each hemifield. It is evident that tracking performance declines significantly when adding two more targets in the same hemifield but not in the opposite hemifield. In Experiment 2, when each of two targets were presented in opposite hemifields we found no significant decrement in speed limits as the number of tracked targets increased from one to two. This finding might be explained by the hemisphere-specific resource theory. But in Experiment 2 we only provide semi-evidence for the theory and are not sure whether there is huge decrement on speed limit for adding another target in the same hemifield. For the next chapter (Chapter 3), we will address this uncertainty with some experiments and discuss more about the hemisphere-specific resource theory.

The capacity-one benchmark might be used to provide another interpretation for the hemisphere-specific resource theory. Capacity-one benchmark was calculated to predict the two-target speed limit if participants can track only one target and need to guess the other. Only Experiment 2 found the empirical speed limit for tracking two targets to be higher than that predicted by the capacity-one benchmark, indicating the tracking capacity is more than

one target. In Experiment 2 targets were presented in opposite hemifields. This finding might suggest that there are two independent tracking resources, and each target is supported by one hemisphere-specific resource. Thus, observers can simultaneously track more than one target at high speeds.

Conversely, if two targets are tracked by a common resource and if observers can track only one target at high speeds, the empirical speed limit for tracking two targets should be similar to or lower than that predicted by the capacity-one benchmark. We suggest that the reason for a lower speed limit than capacity-one benchmark when tracking two targets is that participants split this common resource in attempting to track both targets, and may end up unable to track any target at high speeds. In both Experiments 1 and 3, targets move with two concentric circular trajectories in the centre of visual field, which are across two separate hemifields. The observed speed limit for tracking two targets was lower than that predicted by the capacity-one benchmark. The reason of this finding might be caused by the display of these two experiments involved both two independent hemisphere-specific resources, and at high speeds, collaboration of both hemisphere-specific resources can only supported for tracking one target.

## **2.6 Conclusion of Chapter 2**

In summary, we provided evidence for a number of tracked targets effect on object tracking speed limits, whilst minimizing spatial interference by utilizing widely separated objects or equating cumulative object travelled distance. The speed limit declined when the number of tracked targets increased. We suggest that the capacity-one benchmark provides a useful method in demonstrating the resource theory of multiple object tracking.

## **Chapter 3 : Tracking Resource is Hemisphere-Specific**

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### **3.1 Introduction of Chapter 3**

The main topic of Chapter 2 was the resource costs of tracking fast-moving objects. We showed that splitting the tracking resource among multiple targets reduces the tracking speed limits. By utilizing widely separated objects to avoid spatial interference, and equating the cumulative distance that objects travel to equate the occurrence of spatial interference in the experiments of Chapter 2, we found strong support for the resource theory. The maximum target speed at which participants were able to track two targets was significantly slower than the speed at which they were able to track one. The speed limit for tracking two targets was approximately equal to what was predicted if, at high speeds, only a single target could be tracked, which is also consistent with a linear resource-versus-performance function. This suggests that performance with a fast-moving target is very sensitive to the amount of resource allocated. These results cannot be accommodated by the FINST or interference theories.

#### **3.1.1 Hemisphere Specificity**

The attentional resource involved may be a general central pool allocated to targets at anywhere in the visual field. Alternatively, there may be two independent hemisphere-specific resource pools in our brain, with the tracking resource in the left hemisphere devoted to stimuli in the right visual hemifield and the resource in the right hemisphere devoted to stimuli in the left visual hemifield. Previous studies have suggested there are independent attentional resource pools in the left and right cerebral hemispheres of split-brain patients, inducing a faster processing of a visual search task in bilateral displays than in unilateral displays (Luck et al., 1989). Each hemisphere can process information independently with its own resource (Friedman & Polson, 1981).



The factors that limit tracking, such as target speed and number, appear to operate largely independently in the left and right visual fields, suggesting that if a resource does mediate tracking, there are two independent pools, one in each cortical hemisphere. Alvarez and Cavanagh (2005) presented a target in one visual hemifield and tested the effect of adding another target in the same hemifield or in the opposite hemifield. Performance was much poorer when the additional target was presented in the same visual hemifield, but not significantly affected when the second target was presented in the opposite hemifield. This suggests that the tracking resource consumed by additional targets is hemisphere-specific.

A concern with the Alvarez and Cavanagh (2005) finding was that some or all of the decrease in performance with additional targets may have reflected spatial interference rather than resource depletion. It was not clear how much of the effect was resource related and how much was owed to crowding. Crowding effects can certainly play a role in object tracking, by decreasing the accuracy of tracking results because objects cannot be individuated when they pass close together (Intriligator & Cavanagh, 2001). In the Alvarez and Cavanagh (2005) study, the objects could pass very close to each other. Since spatial interference (crowding) is known to be greater when objects are presented unilaterally rather than split across hemifields (Liu et al., 2009), the observed decrease in tracking performance when the targets were presented unilaterally might have been caused by spatial interference.

In Chapter 2, Experiment 2 demonstrated no significantly deleterious effect of a second target when the two targets were presented across the vertical meridian, one in each hemifield, suggesting that the tracking performance might be explained by the hemisphere-specific resource theory. The purpose of this chapter investigates whether a hemisphere-specific resource is consumed when speed is increased under conditions of no or minimal crowding and spatial interaction effects.

### 3.1.2 Capacity-one benchmark

Our previous experiments in Chapter 2 measured the maximum speed at which a target could be tracked as a function of the number of targets in the display. Our finding that this speed limit decreased as the number of targets increased indicates that the targets shared a common tracking resource. While we were not able to determine the quantitative mapping between the speed limit and the amount of resource consumed by each target, we were able to predict what would occur if tracking one target consume *all* the resource, with nothing left for a second target. We term this the “capacity-one benchmark”.

The capacity-one benchmark calculates the performance level a participant would have if he attended to just one of the targets and completely ignored the second target. This was described in detail in the *Data Analysis* section of Experiment 1 (Chapter 2). The capacity-one benchmark allows one to put any cost of splitting attention into perspective by comparing the cost to what would occur if participants could only track one object. For example, all of the experiments in Chapter 2 compared the speed limits for tracking one versus two targets. The speed limit for tracking two targets was approximately that predicted by the capacity-one benchmark. This suggests that performance with a fast-moving target is very sensitive to the amount of resource allocated. As explained in Chapter 2, the capacity-one benchmark makes the same prediction as the made by the linear resource-versus-performance function. Most experiments in Chapter 2 found the empirical performance for tracking two targets was lower than that predicted by the capacity-one benchmark. It indicated that successful tracking (>68% accuracy) at high speeds requires more than 50% of the resource. The capacity-one benchmark provides a useful benchmark for putting speed limit changes in perspective. Therefore, in this chapter we also apply this capacity-one benchmark to evaluate the resource costs on one visual hemifield.

The purpose of this chapter is to confirm whether a hemifield-specific resource mediates tracking, with crowding and spatial interaction effects minimized. Our Experiment 4 addressed this issue by using a display in which the objects were kept widely separated to avoid crowding. In Experiment 4, we measured the speed limit by asking observers to track one target in one single hemifield, and then tested how this speed limit was affected when observers were asked to track an additional target in either the same or opposite hemifield.

However, the duration of the trials in Experiment 4 did not differ for different speeds, so for trials testing fast target speeds, the targets travelled much further than on slow-speed trials. Franconeri et al. (2010) pointed out that with this type of design, high-speed trials may be associated with more spatial interference because the targets pass relatively near each other on more occasions. In the display configuration of Experiment 4, the objects were always far from each other, so spatial interference seems unlikely, but nevertheless we sought to exclude this possibility here. Accordingly, in Experiments 5 and 6, we equated the distance travelled across speeds.

Franconeri (2013) suggested that the reason for hemifield independence of tracking is not because of a hemisphere-specific resource, but rather a lack of spatial interference across the vertical midline. That is, Franconeri suggests that two targets are generally harder to track than one because the cortical representations of nearby objects interfere with each other, and that this occurs at a stage where competition does not occur across the hemispheres. Although there may be no empirical evidence supporting this suggestion, we sought to test it nonetheless. Our Experiment 7 investigates whether there is an effect of spatial interference on speed limits by varying the separation between targets within one single hemifield. With this display, little to no effect of separation was observed, which favours the hemisphere-specific resource theory of hemifield independence rather than the spatial interference theory.

### **3.2 Experiment 4: Testing Hemifield Specificity of the Tracking Resource**

The purpose of Experiment 4 is to investigate whether the hemisphere-specific resource is also consumed by increasing speeds when crowding and spatial interaction effects are minimized.

According to the theory of two hemisphere-specific resource pools, if two targets are presented in the same visual hemifield, the speed limit should be lower than when the two targets are presented in different hemifields. This hypothesis is based on the prediction that for two targets in the same hemifield, only one hemisphere-specific resource is available for the two targets, so each target receives half of the hemisphere-specific resource. If instead the second target is presented in the opposite hemifield, there should be little effect on speed limit of the additional target (as it will receive the hemisphere-specific resource allocated to that visual hemifield).

#### **3.2.1 Method**

##### **3.2.1.1 Participants**

Eight people (six male, two female, 29-38 years of age) who reported normal or corrected-to-normal vision agreed to participate, following approval of the protocol by the University of Sydney's ethics committee. All had extensive experience fixating in laboratory experiments.

##### **3.2.1.2 Stimuli**

A 120 Hz CRT displayed four red blobs (evoked by the red gun only, with Gaussian intensity profiles; visible diameter 1 deg; peak luminance 20 cd/m<sup>2</sup>) and a white fixation point against a black background, at a viewing distance of 57 cm. The spatial arrangement of the objects is schematized in Figure 3.1. Two pairs of blobs were presented in all conditions. Each pair moved on a circular trajectory that was centred in one of the four quadrants of the visual field. The two pairs of blobs were placed in either the same hemifield (unilateral

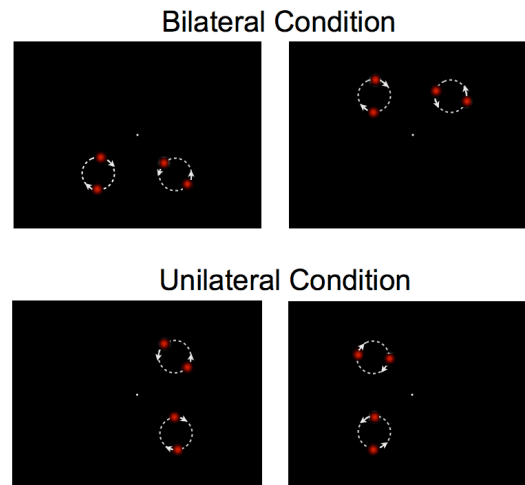
condition) or opposite hemifields (bilateral condition). Each circular trajectory was centred on a point 6 deg from the vertical midline and 6 deg from the horizontal midline (one of the four quadrants). For the unilateral condition, in half of trials, the two pairs were placed in the left visual field and in the other half of trials in the right visual field. For the bilateral condition, in half of trials the two pairs were placed in the upper visual field and in the other half of trials in the lower visual field. The radius of each trajectory was 2.5 deg, and because the two blobs on a trajectory were always diametrically opposed, the separation between them was always 5 deg. According to studies of crowding, these distances should be large enough to avoid spatial interference (Intriligator & Cavanagh, 2001; Pelli & Tillman, 2008).

### **3.2.1.3 Procedure**

Observers were told to maintain fixation on the white dot at the display centre. To indicate which blobs were targets, for the first 0.7s of the motion interval the colour of the targets was white instead of red. The tracking period followed this, during which all objects were red. To prevent participants from predicting the final target positions from their initial positions and speeds, the blobs occasionally reversed direction. Each pair of blobs was independently assigned a series of reversal times, which succeeded each other at random intervals between 1.2 and 2 s. After the tracking period, which was randomly set to between 3 and 3.8 seconds (including 2 or 3 reversals of each pair of blobs), all four blobs stopped rotating (Figure 3.2).

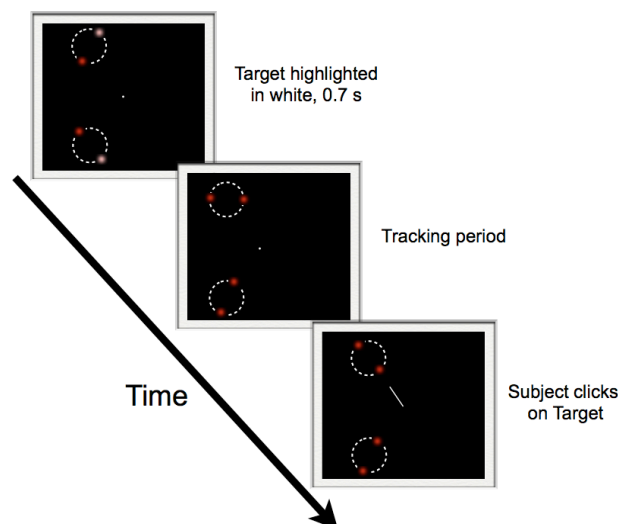
In this experiment, observers were asked to track one or two targets. In the one-target condition, only one blob was designated as a target. For the unilateral arrangement, for half of trials the target was in the upper ring and in the other half it was in the lower ring. For the bilateral arrangement, for half of trials the target was in the right ring and in the other half it was in the left ring. In the two-target condition, one blob of each ring began white to designate them as targets.

At the end of the trial, one pair of blobs was indicated with a white line and the participants used the mouse to indicate which of the two blobs was the target. In the two-target condition, in half of trials participants were asked to indicate the target at the upper (right) ring and in the other half of trials were at the lower (left) ring for the unilateral (bilateral) arrangement.



**Figure 3.1. Display of Experiment 4**

In Experiment 4, two pairs of blobs were presented in each condition. Each pair moved along a circular trajectory (dotted lines) and was centred in one quadrant. They were presented in one of two conditions: at the left or right side of the vertical meridian (unilateral condition), and above or below fixation (bilateral condition). A blob from one or both pairs was designated as targets.



**Figure 3.2. A schematic of the trial sequence for all experiments in Chapter 3**

After the targets are highlighted in white for 0.7s, all blobs become red and revolve about their rotation centre. During this interval, the pair of blobs on each trajectory occasionally reverses movement direction, at random times independent of the other pair. After tracking period the blobs stop, one ring is indicated by a white line, and the participant clicks on one blob of that ring.

All objects revolved at the same rate throughout each trial. Five rotation rates were used on different trials, which were presented in pseudorandom order and fully crossed with the one-target versus two-target conditions. The speeds for each condition and person were chosen on the basis of piloting. Each observer participated in 192 trials at each of the five rates. Observers were presented with 960 experimental trials in total, divided into six sessions. Each participant did no more than two sessions a day and observers had a minimum break between sessions of 5 minutes.

#### **3.2.1.4 Data Analysis**

Plots of speed versus proportion correct were fit by a logistic regression that spanned from chance (50% accuracy) to a ceiling level of performance. The ceiling performance corresponds to the lapse rate, which in the fitting procedure was allowed to vary from 0% to 10% to get the best estimate. This estimated lapse rate for each condition is reported in the results section. We refer to the speed at which performance is estimated by the regression to fall to 68% correct as the “speed limit”. The regression fit separately for each participant, as well as the condition set to estimate the speed limits.

In all experiments of Chapter 2, we calculated the expected effect on speed limits of increasing the number of targets, under the seemingly worst-case assumption that observers could track only one target, and had to guess on the trials where they were queried on the untracked target. In fact, this capacity-one benchmark is not the worst-case scenario, because the resource-versus-performance function might fall below the linear function. In that case if participants attempt to track both targets, performance will fall below the capacity-one benchmark. Here we extend this benchmark by assuming that participants can track only one target in each hemifield rather than within whole visual field.

A prediction of the hemisphere-specific resource theory is that adding targets to the opposite hemifield will have no effect whereas adding targets to the same hemifield should

worsen performance. As far as we know, this is the only prediction tested by other authors (e.g. Alvarez & Cavanagh, 2005; Carlson et al., 2007). Hemisphere-specific resource theory also makes a stronger claim: that very demanding (high-speed) targets will exhaust the resource and therefore participants will be completely unable to track additional targets per hemifield. In other words, performance will be well described by the capacity-one benchmark.

Calculation of the prediction of the hemisphere-specific capacity-one benchmark in the present circumstances proceeded as follows. In each visual hemifield, it is assumed that the observer tracks only one target. Thus, for the two-target condition, in half the trials the observer will by chance have tracked the target in the pair that is queried. For these trials the predicted performance for that speed is provided by the one-target logistic curve. In the other half of the trials the observer will have been queried about one of the pairs that he did not track. Consequently, the observer will be forced to guess which of the blobs is the target and therefore performs at chance (50%). The resulting psychometric function yields the predicted speed limit (68% threshold) for the two-target condition. This prediction is shown as the dotted bars in Figure 3.4.

For slow target speeds, actual performance for tracking two targets is higher than the capacity-one benchmark, in the present data as well as in experiments of Chapter 2. This shows that at slow speeds, participants can track more than one target in each visual hemifield. At high speeds however, actual performance is similar to the benchmark. Previously assessing the speed at which performance fell to the “speed limit” level of performance (68% correct), in Chapter 2, we found that the capacity-one benchmark speed limit was not significantly different than that of the data. This indicates that participants did no better than they would if they tracked only one single target in each visual hemifield.



If anything, the observed speed limits were even worse than those of the capacity-one benchmark (this statistically non-significant trend was also seen in the data of experiments in Chapter 2). This indicates that devoting half of the resource to a target yields only very poor performance in each target (parallel resource theory). If dividing one's resource between the targets frequently results in failure to successfully track any of them, one would be better off attempting to track only one. This may be the strategy participants occasionally adopted (serial switch theory).

### 3.2.2 Results and Discussion

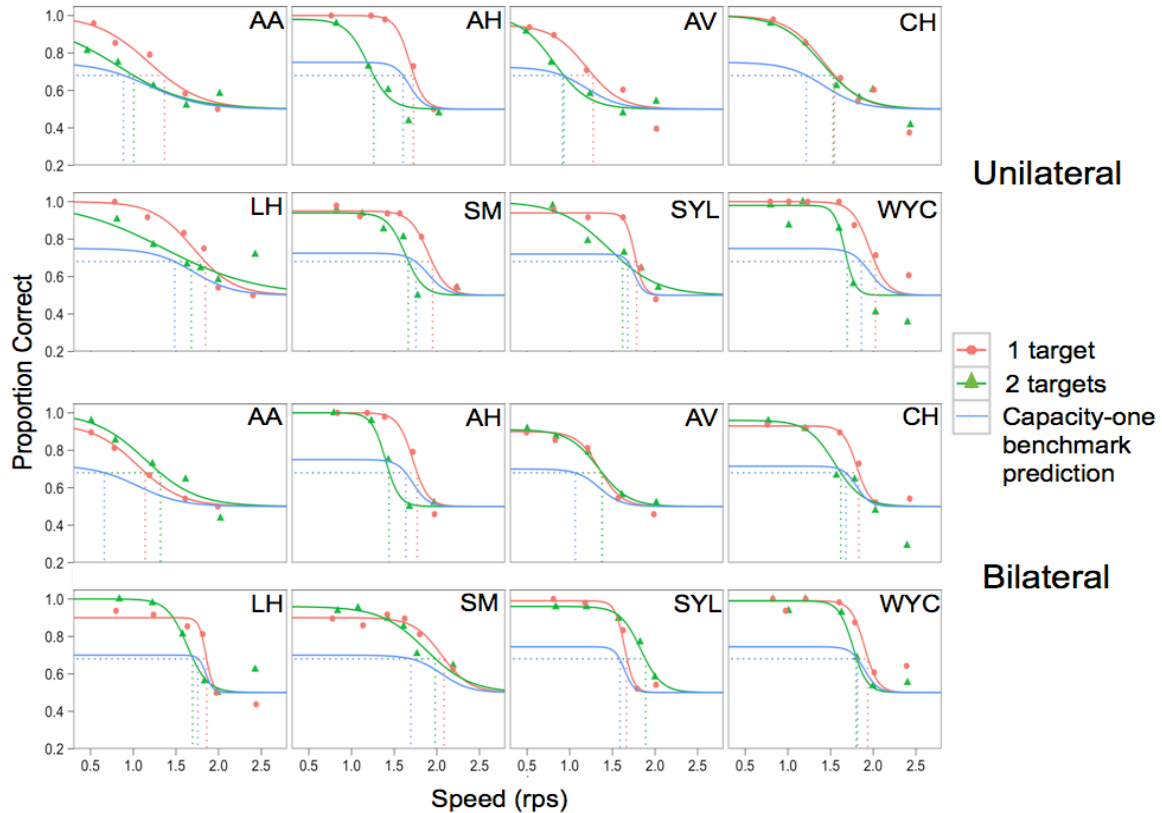
The data and fitted curves are shown for each participant in Figure 3.3, with the associated speed limits (68% thresholds) shown in Figure 3.4.

Results were compatible with the hemisphere-specific resource theory in that tracking performance was better when two targets were presented in the separate hemifields than in the same hemifield. A 2 x 2 repeated-measures ANOVA indicated that the speed limit was greater for the bilateral (1.67 rps) arrangement than for the unilateral (1.56 rps) arrangement,  $F(1, 7) = 10.891, p = 0.013$ , partial  $\eta^2 = 0.609$ . Consistent with resource theory, the speed limit for tracking one target (1.70 rps) was substantially higher than for tracking two targets (1.53 rps),  $F(1, 7) = 14.719, p = 0.006$ , partial  $\eta^2 = 0.678$ .

The hemisphere-specific resource theory predicts a significant interaction of the two factors (arrangement and number of tracked objects). Specifically, the advantage of the bilateral arrangement should be greater for the two-target condition than for the one-target condition. This was indeed the result according to a repeated-measures ANOVA,  $F(1, 7) = 5.924, p = 0.045$ , partial  $\eta^2 = 0.458$ . The speed limit for the one-target condition was very similar whether the other pair of blobs is in the same hemifield (1.69 rps) or the other hemifield (1.71 rps), and no significant difference was found by a paired-t test,  $t(7) = 0.328, p = 0.753$ , Cohen's  $d = 0.064$ . This suggested that in the one-target condition, there was no

differential distracting or masking interference caused by the irrelevant pair of blobs.

However, there was a large difference in speed limit between bilateral (1.64 rps) and unilateral arrangements (1.42 rps) when observers tracked two targets, paired t-test,  $t(7) = 4.243$ ,  $p = 0.004$ , Cohen's  $d = 0.772$ .



**Figure 3.3. Individuals' performance in Experiment 4**

For each participant in Experiment 4, proportion correct is plotted against speed, for the bilateral and unilateral conditions, in the one-target (red) and two-target (green) conditions. The blue line shows the two-target prediction based on the assumption that the participant could only track one target. Dotted lines show the speed limits (68% thresholds).

There is no specific difference on speed limits among visual fields. For the unilateral condition, whether the objects are on the left or the right had no significant effect on speed limit for tracking one (Right:  $M = 1.74$  rps; Left:  $M = 1.66$  rps,  $t(7) = 0.707$ ,  $p = 0.502$ , Cohen's  $d = 0.226$ ) or two targets (Right:  $M = 1.37$  rps; Left:  $M = 1.49$  rps,  $t(7) = -1.113$ ,  $p = 0.302$ , Cohen's  $d = -0.313$ ). For the bilateral condition, a paired-t test also indicated no statistically significant difference between the speed limit of upper and lower visual hemifields in the one (Upper:  $M = 1.69$  rps; Lower:  $M = 1.67$  rps,  $t(7) = 0.792$ ,  $p = 0.454$ , Cohen's  $d = 0.082$ ) or two

targets (Upper:  $M=1.64$  rps; Lower:  $M=1.62$  rps,  $t(7)=0.322$ ,  $p=0.757$ , Cohen's  $d=0.068$ ) tracking conditions.

So far we have considered only the simple qualitative prediction of hemisphere-specific resource theory—that adding targets to the opposite hemifield has no effect whereas adding targets to the same hemifield worsens performance. Given that targets within the same hemifield share the same hemisphere-specific tracking resource, the question arises of how much resource is needed to accurately track a target. This cannot be measured directly, but we can compare performance to the prediction of the linear resource-versus-performance function. The capacity-one benchmark makes the same prediction for the cost of adding a second target, that performance will fall halfway to chance.

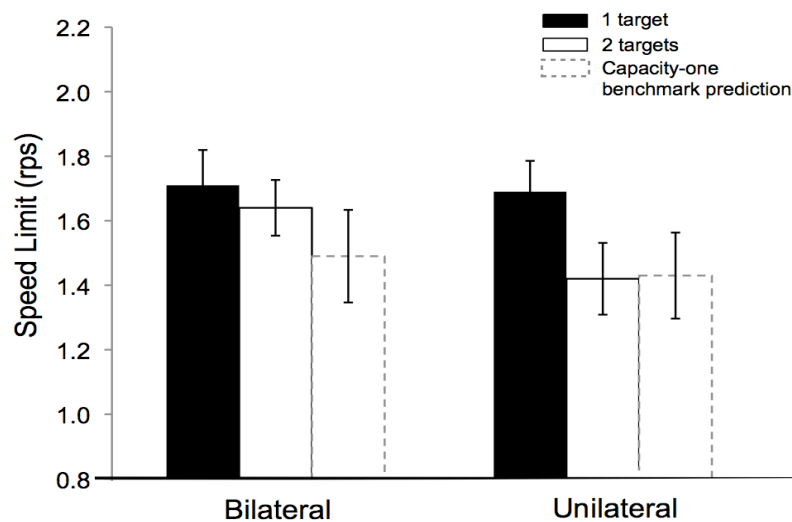
At low target speeds, performance is clearly much better than the capacity-one benchmark. Indeed at very low speeds participant performance is near 100% correct. The estimated lapse rate for tracking two targets is around .03 for both bilateral and unilateral arrangements, suggesting that the psychometric function saturates at 97%. If participants could only track one target in each hemifield (the capacity-one benchmark) performance should never exceed 75% correct for tracking two targets at that hemifield. This indicates that participants are capable of tracking both targets when they move slowly no matter stimuli were presented in the same or separate hemifields.

Although observers actually did not ignore any of the targets during the tracking event, the performance level provides some information about the resource-versus-performance function. Reducing the resource available for a target from 100% (one target per hemifield) to 50% (two targets per hemifield) has little effect on performance. The first reaction of many expert readers may be that this is a ceiling effect. That's our point. At slow speeds, tracking is very accurate (near ceiling) whether 50% or 100% resource is used (flat resource-versus-performance function in this domain).

For high target speeds, we suspected that tracking would be increasingly resource-demanding, meaning that adding a target to each hemifield would be costly. The hemisphere-specific resource theory was partially supported by comparing the results to the capacity-one benchmark predictions. As shown by the rightmost grey dotted bar in Figure 3.4, in the unilateral condition, the measured speed limit for tracking two targets (1.42 rps) was not significantly different from that predicted (1.43 rps) by the capacity-one benchmark, as revealed by a paired t-test,  $t(7) = -0.025$ ,  $p = 0.981$ , Cohen's  $d = -0.005$ . This suggests that performance at these high speeds then was as deficient as if participants simply ignored the second target in each hemifield. Another suggestion from the linear resource-versus-performance function is that when the amount of resource allocated to one target decreases from 100% to 50%, the speed limit of that target significantly declines from 1.7 rps to 1.42 rps. In the bilateral condition, the two-target speed limit (1.64 rps) was higher than that predicted (1.49 rps) but this was not statistically significant, according to a paired t-test,  $t(7) = 1.534$ ,  $p = 0.169$ , Cohen's  $d = 0.459$ . The difference between the empirical and predicted two-target speed limit was not significantly larger for the bilateral condition than the unilateral condition according to a paired t-test,  $t(7) = 1.383$ ,  $p = 0.209$ , Cohen's  $d = 0.624$ . It might suggest that the resource is not 100% hemisphere-specific. This suggestion was also supported by the fact that the speed limit for tracking one target was slightly higher than tracking two targets in the bilateral condition. Even still, these findings were not statistically significant as revealed by a paired t-test,  $t(7) = 0.998$ ,  $p = 0.351$ , Cohen's  $d = 0.243$ .

In Experiment 1 of Chapter 2, we also examine the lapse rates of the fits in all conditions to test for a larger sign of spatial interference in the unilateral arrangement than found in the bilateral arrangement. A repeated-measures ANOVA was conducted with hemifield arrangement and target number as the independent variables and lapse rate the dependent variable. The ANOVA indicated that target number ( $F(1, 7) = 4.845$ ,  $p = 0.064$ ,

partial  $\eta^2=0.409$ ) and hemifield arrangement ( $F(1, 7)=4.54, p=0.071$ , partial  $\eta^2=0.393$ ) was not significant, nor the interaction of target number and hemifield arrangement ( $F(1, 7)=1.253, p=0.3$ , partial  $\eta^2=0.152$ ). Contrary to what would be expected from spatial interference, the lapse rate was actually higher in one of the one-target conditions than in either of the two-target conditions: one-target bilateral (lapse rate=0.06), one-target unilateral (lapse rate=0.02), two-target bilateral (lapse rate=0.03), and two-target unilateral (lapse rate=0.02).



**Figure 3.4. Averaged Speed Limits in Experiment 4**

Here we see the mean speed limits (68% thresholds) for tracking one and tracking two targets in the unilateral and bilateral condition. The two-target cost is significantly greater in the unilateral condition than in the bilateral condition, indicating that the resource that determines the speed limits is at least partially hemisphere-specific. The grey dotted bars show the two-target prediction based on the assumption that the participant could only track one target.

### 3.3 Experiment 5: High Loads (2 Vs. 4 targets) with Constant Travelled Distance.

In Experiment 4, the speed limit decreased substantially when tracking shifted from one target to tracking two targets if both targets occupied the same hemifield. If the second target was instead placed in the opposite hemifield, little decrement in the speed limit occurred (also shown in Experiment 2). This supports the claim of an existent tracking resource that is independent in each hemifield, and the hemisphere-specific resource that is also consumed by increasing speeds. In addition, the speed limit for tracking two targets in

the same hemifield was similar to if participants had ignored one of the targets and simply guessed whenever it was probed.

As a concern in Experiments 2 and 3, spatial interference might explain the target number effect on speed limit by appealing to the possibly greater opportunity for spatial interactions when the stimulus was presented at high speeds (Franconeri et al., 2010). This opportunity arises because in the high-speed trials, the targets went about the circular trajectory many more times and thus came relatively close to the other target more times. The hemifield effect on speed limit for tracking two targets in Experiment 4 might be confounded with more spatial interference in the unilateral condition owing to longer accumulative objects travel distance at higher speeds. In Experiment 5, we equated the total travel distance across speeds to exclude this confound.

The hemisphere-specific resource theory was also supported by two previous studies with higher tracking load (Alvarez & Cavanagh, 2005; Battelli, Alvarez, Carlson, & Pascual-Leone, 2009). Performance for tracking two targets in one visual hemifield was not significantly affected by a requirement to track additional two targets in the opposite hemifield. However, both of their results did not rule out the confound of spatial interference. To verify that the hemisphere-specific resource theory also accommodates for tracking targets at high load, in Experiment 5, we increase the target number load from one versus two to two versus four.

According to the hemisphere-specific resource theory, it is hypothesized that compared to two targets in opposite hemifields (bilateral condition), adding two more (one in each hemifield), should have a large cost (four-target condition) for the speed limit. The cost should be as large as predicted if participants could only track one in each hemifield at high speed and had to ignore the other, just as in Experiment 4. Compared to two targets placed in

a single hemifield (unilateral condition), adding two more in the other hemifield (four targets condition) should have no significant cost.

### **3.3.1 Method**

#### **3.3.1.1 Participants**

Five participants (four male, one female, 24-31 years of age) who reported normal or corrected-to-normal vision agreed to participate, and four of them also participated in Experiment 4.

#### **3.3.1.2 Stimuli**

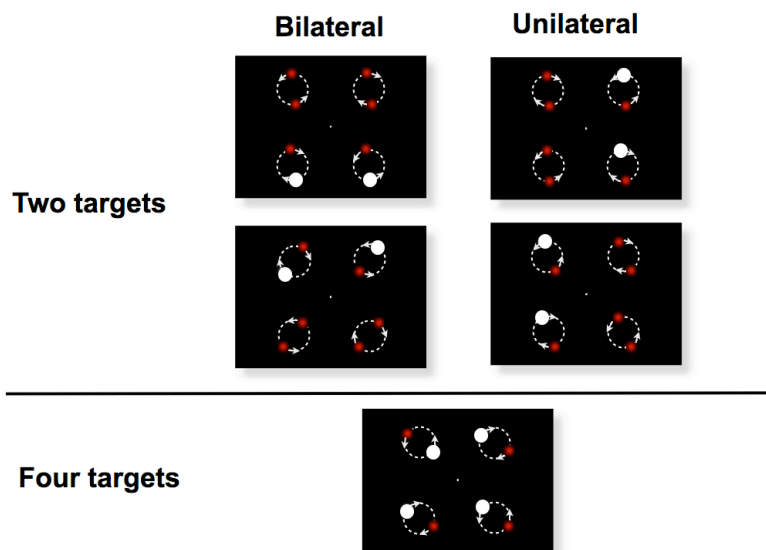
The apparatus and stimuli used were identical to those of Experiment 4 except for the few changes described here. Whereas in Experiment 4 only two pairs of blobs were presented on the monitor, in Experiment 5, four pairs of blobs were presented, each located in one of four quadrants of the visual field. The spatial arrangement of the blobs is schematized in Figure 3.5. In the four-target condition, one blob of each pair was designated as a target to be tracked. In the two-target bilateral condition, the two target pairs were both above the fixation point in half of the trials and both below in the other half. In the two-target unilateral condition, the two target pairs were either both to the left of the fixation point or both to the right of the fixation point.

#### **3.3.1.3 Procedure**

The sequence of events was identical to that of Experiment 4 but there was a difference in how the duration of the trials was set. To avoid the possibility of more opportunities for spatial interference at higher speeds, the cumulative distance travelled by the blobs was the same for all trials. This was achieved by setting the duration of the trial to a different value for each speed condition. All objects revolved at the same rate. Across trials, five rotation speeds (0.7, 1.0, 1.4, 1.7, and 2.2 rps) were used, and to achieve a constant

distance travelled of 6.6 revolutions, this yielded five corresponding tracking durations (9.4, 6.6, 4.7, 3.9, 3s).

Each observer participated in 160 trials at each of the five rates, yielding 800 experimental trials in total, divided into five sessions. Conditions were mixed, each observer did no more than two sessions a day, and observers had a minimum break between sessions of 5 minutes.



**Figure 3.5. Schematic of the displays in Experiments 5 and 6**

Four pairs of red blobs were presented in each condition. Each pair moved along a circular trajectory (dotted lines) centred in one quadrant, and potentially included a target. The targets were presented in one of three conditions: two targets to the left or the right side of the vertical meridian (two-target unilateral), two above or below the vertical meridian (two-target bilateral), or four targets with one in each quadrant (four targets). The targets were initially white before becoming red like the distractors.

### 3.3.1.4 Data Analysis

The data was analysed as in Experiment 4, with speed limits (68% thresholds) extracted from the psychometric curve fit.

Similar to Experiment 4, we used a hemifield-independent version of the capacity-one benchmark to predict the speed limit in the four-target condition. According to this benchmark, in each visual hemifield the observer tracks only one target. Thus, in half the trials the observer will by chance have tracked the target in the pair that is queried. For these trials the predicted performance for that speed is provided by the bilateral two-target logistic



curve fit (as this corresponds to the situation where there is only one target in each hemifield). In the other half of the trials the observer was queried about one of the pairs that he did not track. Consequently, the observer will be forced to guess which of the two blobs is the target and therefore performs at chance (50%). The resulting psychometric function yields the predicted speed limit (68% threshold) for the four-target condition. This prediction was shown as the upper red dotted bar at the bottom of Figure 3.6.

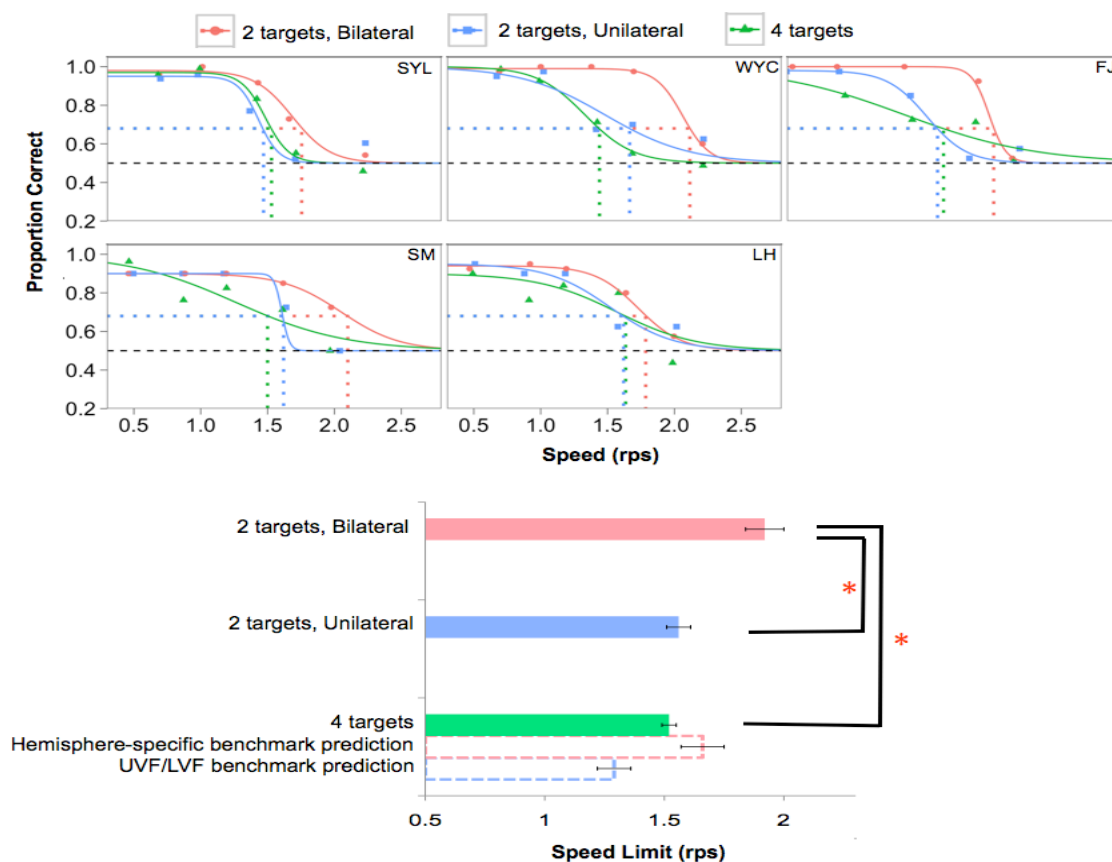
An alternative and unlikely hypothesis, but an instructive one for the contrasting prediction that it makes, is that observers track objects independently in the upper and lower visual hemifields (UVF and LVF, respectively), and can only track one object in each. For this UVF/LVF capacity-one benchmark, in the four-target condition, performance on half of the trials would be given by the unilateral two-target condition, and by the chance level on the other half of trials. This predicted speed limit is shown by the lower blue dotted bar at the bottom of Figure 3.6.

### 3.3.2 Results and Discussion

The data and fitted curves are shown for each participant in the top panel of Figure 3.6, with the associated speed limits (68% thresholds) shown at the bottom panel. For two targets, consistent with the hemisphere-specific resource theory, the speed limit was better in the bilateral arrangement (1.92 rps) than in the unilateral arrangement (1.56 rps). This difference was statistically significant according to a paired t-test,  $t(4) = 6.096$ ,  $p = 0.004$ , Cohen's  $d = 2.499$ .

Also as predicted by the hemisphere-specific resource theory (as compared to the speed limit for tracking two targets in a single hemifield), adding two more targets in the opposite hemifield had little to no effect on the speed limit (1.56 rps vs. 1.52 rps,  $t(4) = 0.816$ ,  $p = 0.46$ , Cohen's  $d = 0.492$ ).

When compared to having one target in both the left and right hemifield, tracking a second target in each hemifield was expected to increase the load on each hemisphere-specific resource. Consistent with this, the speed limit cost was large, from 1.92 rps to 1.52 rps- a significant difference-  $t(4) = 3.959, p = 0.017$ , Cohen's  $d = 3.018$ . This cost (0.41 rps) was significantly larger than the (non-significant) cost of adding targets in the opposite hemifield described in the previous paragraph (0.05 rps), as indicated by a paired t-test on the difference of the speed limit differences,  $t(4) = 6.096, p = 0.004$ , Cohen's  $d = 1.96$ .



**Figure 3.6. Results of Experiment 5**

**Top panel.** For each participant, proportions correct are shown for each speed in the two-target bilateral (red), two-target unilateral (blue) and four-target (green) conditions. Dotted lines show the 68% thresholds (speed limit). **Bottom panel.** Empirical speed limits for tracking two and four targets, and the speed limit predicted for four targets by the capacity-one benchmark using the hemisphere-specific resource assumption and the (expected to be wrong) upper/lower field resource assumption. Error bars show one standard error across participants. Red stars show the statistically significant difference between conditions ( $p < 0.05$ ).

A non-significant trend was present for a poorer speed limit for the four targets condition than for the unilateral two-target condition, indicating that in the latter condition both the ipsilateral and contralateral hemispheres might have contributed to tracking the

targets. A similar non-significant effect was observed in Experiment 4. These non-significant trends suggest that the tracking resource may not be 100% hemisphere-specific.

Similar to Experiment 4, we also compared the empirical performance for tracking two targets within one hemifield with the predicted performance by the capacity-one benchmark. As described in the Method section, this calculation was based on the performance in the two-target bilateral arrangement. The .04 lapse rate for 4-target condition further indicates when targets move very slowly, participants are capable of successful tracking not only two targets within one single hemifield (shown in Experiment 4) but also four targets within a whole visual field with near perfect performance.

For high target speeds, we calculated the speed limit of the capacity-one benchmark. This benchmark speed limit was shown by the upper red dotted bar at the bottom of Figure 3.6. The measured speed limit for tracking four targets (1.52 rps) was not significantly different from that the benchmark (1.66 rps), as revealed by a paired  $t$ -test,  $t(4) = -1.249$ ,  $p = 0.28$ , Cohen's  $d = -0.982$ . Performance at these high speeds then was as bad as if participants simply ignored the second target in each hemifield.

As a further validation of the hemisphere-specific resource theory and the resemblance of the results to the capacity-one benchmark, we document here how discrepant the results are from the alternative assumption that observers tracked objects independently in the upper and lower hemifields and within each only one target could be tracked. We call this the UVF/LVF capacity-one benchmark prediction (lower blue dotted bar in Figure 3.6). As we described in the Method section, this amounted to calculating a benchmark four-target speed limit using the performance data from the two-target unilateral arrangement and combining it with guessing in half of trials. As shown in Figure 3.6, the predicted speed limit (1.29 rps) was significantly lower than the measured four-target speed limit (1.52 rps), paired

$t(4) = 2.923, p = 0.043$ , Cohen's  $d = 1.873$ , suggesting that the tracking resources are not specific to the upper and lower visual hemifields.

While the large speed limit cost of the additional target in each hemifield is consistent with resource theory, it does not particularly support spatial interference theory. Spatial interference theory does not make the specific prediction that the effect of additional targets should be as large as that predicted by the capacity-one benchmark. Because the objects were always widely spaced, it seems that spatial interference theory would predict only a small effect on speed limit, if any.

According to spatial interference theory (Franconeri et al., 2010; Franconeri et al., 2008), the detrimental effects of additional targets should be equivalent across speeds if the total distance travelled by the objects is constant. Therefore, performance should be poorer (even at slow speeds) in the four-target condition, than in the two-target bilateral condition. This would manifest as an increase in the “lapse rate” parameter in our psychometric function fit. This parameter represents the ceiling performance level. If spatial interference impairs tracking, it should further reduce accuracy for conditions with higher number of targets, thus inflating their lapse rates relative to those conditions with fewer targets.

A repeated-measures ANOVA was conducted with both the condition and subject as the independent variables and lapse rate as the dependent variable. We found no significant differences among the three conditions: two-target bilateral (lapse rate=0.04), two-target unilateral (lapse rate=0.04), and four-target (lapse rate=0.03),  $F(2, 8) = 0.419, p = 0.672$ , partial  $\eta^2 = 0.095$ . These results argue against significantly greater spatial interference when more targets are tracked.

### **3.4 Experiment 6: Eye Tracking and Constant Number of Reversals**

This experiment was motivated primarily by a concern regarding some of the experiments in this thesis, in which the centre of target moving trajectory is not at the central

fixation point instead of at each centre of quadrant, such as Experiments 2, 4 and 5.

Participants may not have maintained accurate fixation on the fixation point. In order to locate the targets closer to the fovea, participants instead might move their fixation toward the midpoint of the two circular trajectories that contained targets. If participants shift their fixation to the midpoint of the two circular trajectories in the right or left hemifield, tracking targets involves both hemispheres instead of just one hemisphere, thus the supportive evidence of the hemisphere-specific resource theory will no longer hold in Experiment 2, 4, and 5. To address this concern, in the present experiment we recorded eye movements with an eye tracker.

In Experiment 5, a second point of interest is that for trials with lower speeds, the number of reversals was greater. Therefore, it is uncertain to what extent the detrimental effect of increased speed was due to speed *per se* or to fewer reversals (if reversals might somehow have benefited performance). To resolve this issue, in Experiment 6 we equated the number of reversals across speeds.

### **3.4.1 Method**

#### **3.4.1.1 Participants**

Six participants (four male, two female, 22-37 years of age) who reported normal or corrected-to-normal vision agreed to participate, and three of them also participated in Experiment 5.

#### **3.4.1.2 Stimuli and Procedure**

The apparatus, stimuli, and procedure used were identical to those of Experiment 5 except for the addition of the eye-tracker and the changes in the reversal times. During the 6.6 revolutions of cumulative distance travelled by the blobs after the target-cuing interval, the blobs changed direction at random successive points of between 2.2 to 3 revolutions, resulting in 2 to 3 reversals. The direction changes for each ring were determined randomly

and independently of those for other rings. Each observer participated in 48 trials at each of the five speeds. This was fewer than in Experiment 5, in order to accommodate the eye-tracker calibration and recalibration time. The speeds for individual observers were chosen on the basis of piloting. The tracking durations were set to achieve a constant distance travelled of 6.6 revolutions. Observers were presented with 240 experimental trials in total, divided into two sessions in two separate days.

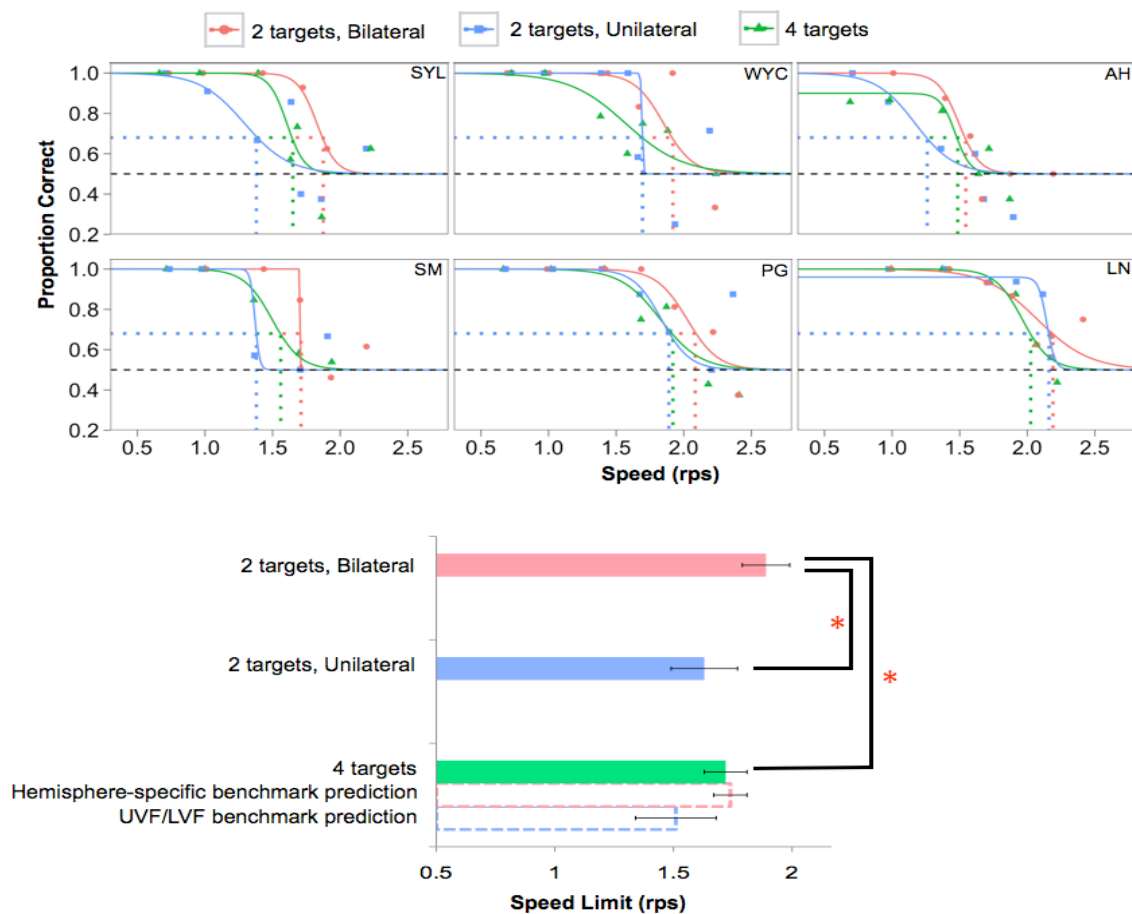
### **3.4.1.3 Eye Tracking**

Eye movements were monitored using an SR Research EyeLink 1000 eye tracker and analysed with the Eyelink 1000 software, version 1.5.2. At the beginning of each session, the eye-tracking system was calibrated and validated using the standard five-point calibration. The experimenter monitored the video image of the participant's eye at the beginning of each trial to ensure that the participant fixated and that the eye-tracker continued to report this correctly. The eye-tracker was recalibrated if, during the interval before the trial, it registered the participant's eye location as being away from fixation even though the participant reported fixating. If the eye-tracker indicated that the participant moved his or her eye by more than 2 deg of visual angle from the fixation point, the trial was discarded.

### **3.4.2 Results and Discussion**

The criterion of eye movement greater than 2 deg from fixation led to the exclusion of 8.3% of the trials (SD=3.3% across participants). A repeated-measures ANOVA revealed no significant difference in the numbers of these eye movements across the five speeds,  $F(4, 20) = 2.146$ ,  $p = 0.113$ , partial  $\eta^2 = 0.3$  or the three conditions (two-target bilateral, two-target unilateral, and four-target),  $F(2, 10) = 1.677$ ,  $p = 0.235$ , partial  $\eta^2 = 0.25$ . The ANOVA also showed no significant interaction between these factors,  $F(8, 40) = 0.539$ ,  $p = 0.82$ , partial  $\eta^2 = 0.097$ .

The data and fitted curves are shown for each participant in the top panel of Figure 3.7, with the associated speed limits (68% thresholds) shown at the bottom panel. As in Experiments 4 and 5, the speed limit was considerably higher in the bilateral arrangement (1.89 rps) than in the unilateral arrangement (1.63 rps) for tracking two targets. This difference was statistically significant according to a paired t-test,  $t(5) = 4.126$ ,  $p = 0.009$ , Cohen's  $d = 0.869$ .



**Figure 3.7. Results of Experiment 6**

**Top panel.** For each participant, proportion correct is shown for the two-target bilateral (red), two-target unilateral (blue) and four-target (green) conditions. Dotted lines show the 68% thresholds (speed limit). **Bottom panel.** Speed limits for tracking two and four targets and the speed limit predicted for four targets by the capacity-one benchmark using the hemisphere-specific resource assumption and the (expected to be wrong) upper/lower field resource assumption. Error bars show one standard error across participants. Red stars show the statistically significant difference between conditions ( $p < 0.05$ ).

Consistent with the hemisphere-specific resource theory, compared to the speed limit for tracking two targets in a single hemifield (two targets unilateral condition), adding two more targets in the opposite hemifield (four targets condition) had little to no effect on the

speed limit (1.63 rps vs. 1.72 rps, paired t-test  $t(5) = -1.496$ ,  $p = 0.195$ , Cohen's  $d = -0.329$ ). But compared to the speed limit in the two-target bilateral condition (1.89 rps), the speed limit for the four-target condition was significantly poorer (1.72 rps), paired t-test  $t(5) = 6.653$ ,  $p = 0.001$ , Cohen's  $d = 0.738$ . This is consistent with the hemisphere-specific resource theory.

The capacity-one benchmark puts these speed limit differences in perspective by calculating the result that would occur if participants only tracked one target in each hemifield and ignored the other. The ensuing capacity-one benchmark speed limit was shown by the upper red dotted bar at the bottom of Figure 3.7. Consistent with Experiment 5, the measured speed limit for tracking four targets (1.72 rps) was not significantly different from that predicted (1.74 rps), paired t-test  $t(5) = -0.417$ ,  $p = 0.694$ , Cohen's  $d = -0.09$ . This is consistent with the possibility that the tracking resource in each hemisphere was only sufficient to track one fast target in each hemifield. Due to matching the prediction of linear resource-versus-performance function with capacity-one benchmark in our display, this result is also consistent with each of two targets within one single hemifield receiving 50% of the hemisphere-specific tracking resource.

As in Experiment 5, for further validation of the hemisphere-specific resource theory, we document here how discrepant the results are from the alternative assumption that observers tracked objects independently in the upper and lower hemifields and within each only one target could be tracked (UVF/LVF resource prediction). Here we see the lone difference from Experiment 5- the discrepancy of the observed speed limit (1.72 rps) from the prediction (1.51 rps) did not reach significance although the effect was in the expected direction, paired  $t(5) = 2.276$ ,  $p = 0.072$ , Cohen's  $d = 0.668$  (Figure 3.7). This may reflect the reduced power of this experiment—mainly because of the additional time demands of eye-tracking, it included only 30% as many trials per participant as had in Experiment 5.



### **3.5 Experiment 7: Varying Target-Target Separations within A Hemifield**

Franconeri (2013) suggested that the reason for hemifield independence of tracking is not because of a hemisphere-specific resource, but rather done to a lack of spatial interference across the vertical midline. Our previous experiments (Experiments 4, 5, and 6) however minimized crowding and spatial interaction effects and demonstrated tracking performance is mediated by a hemisphere-specific resource. Equating the total travel distance of objects (Franconeri et al., 2010) and using wide separation between targets (Franconeri et al., 2008) to avoid spatial interference, we found that tracking additional targets worsens performance greatly in the same hemifield but does not affect performance when additional targets were presented in the opposite hemifield.

Shim et al. (2008) demonstrated tracking performance deteriorated greatly when the spacing between two targets was less than 1.12 deg. This indicates that spatial interference occurred at very close spacing, although Shim et al. (2008) did not control for eccentricity. They also documented that the spatial interference does not exist when two targets were presented in separate quadrants, even if these targets moved within the same hemifield. However, Franconeri (2013) proposed that the spatial interference between targets is the only factor impairing tracking performance, even they are very far apart within a hemifield. According to his theory, one would expect there to be an effect of magnitude of the separation, with greater separations yielding better performance throughout whole visual hemifield.

The purpose of this experiment was to test for large-range spatial interference between two targets within a hemifield proposed by Franconeri (2013). Four distinct separations from large (9 deg) to small (3 deg) were used in this experiment. Large-range spatial interference theory predicts that the speed limit for two targets should gradually decline from large to small separation. Franconeri (2013) hypothesized the spatial

interference to be predominantly between targets, which provides a further prediction that in the one-target condition, there will be less effect of separation than in the two-target condition.

### **3.5.1 Method**

#### **3.5.1.1 Participants**

Eight participants (four male, four female, 22-38 years of age) who reported normal or corrected-to-normal vision agreed to participate, and six of them also participated in Experiment 5.

#### **3.5.1.2 Stimuli**

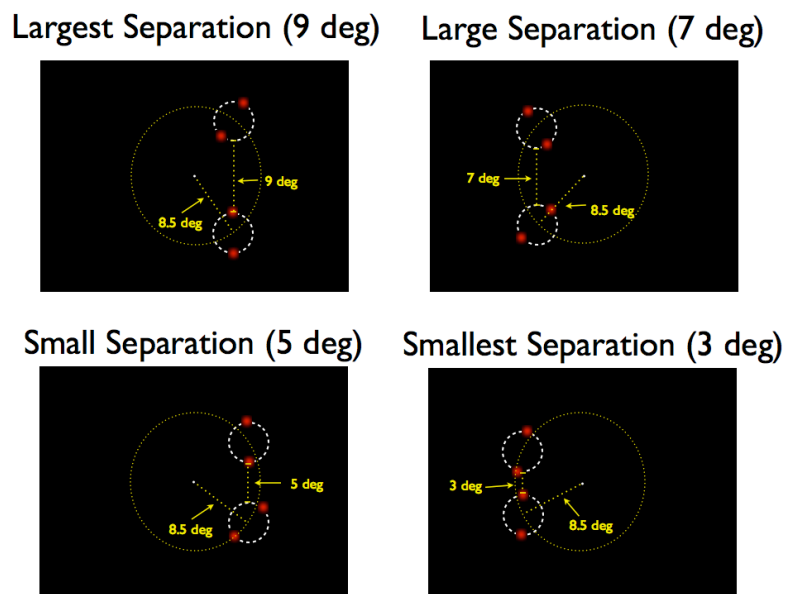
With the following exceptions, the apparatus and stimuli employed were identical to those of Experiment 4. Whereas in Experiment 4, each circular trajectory was centred on a point 6 deg from the vertical midline and 6 deg from the horizontal midline, in Experiment 7 the separation between targets is manipulated by varying the centre of each circular trajectory. Their eccentricity was kept constant, with the centre of each circular trajectory at 8.5 deg. Two pairs of blobs were presented in all conditions and were always in the same hemifield- in half of trials the two pairs were in the left visual field and in the other half of trials they were located in the right visual field. As schematized in Figure 3.8, four separation conditions were used in this experiment. By shifting the pairs up and down, the minimal vertical distance separating the two pairs of blobs was set to 3, 5, 7, or 9 deg. These are the four separation conditions.

#### **3.5.1.3 Procedure**

The sequence of events was identical to that found in Experiment 4. Observers were cued to track one or two targets. In the one-target condition, only one blob was designated as a target. For half of trials, the target was in the upper trajectory and during the other half it was in the lower trajectory. In the two-target condition, one blob of each trajectory was

designated as a target. At the end of the trial, one trajectory was indicated with a white line (see Figure 3.2). The participants used the mouse to indicate which blob was the target in the corresponding trajectory. In the two-target condition, in half of trials participants were cued to indicate the target in the upper trajectory and in the other half of trials they were cued to indicate the target in the lower trajectory.

All blobs revolved at the same speed throughout each trial. A range of speeds from 0.6 to 2.4 rps was used on different trials, presented in pseudorandom order, and fully crossed with the one-target versus two-target conditions. The speeds for each condition and person were chosen on the basis of piloting. Each person participated in at least 640 trials, which usually involved two sessions, each shorter than fifty minutes. The data was analysed as in previous experiments, with speed limits (68% thresholds) extracted from the psychometric curve fit.

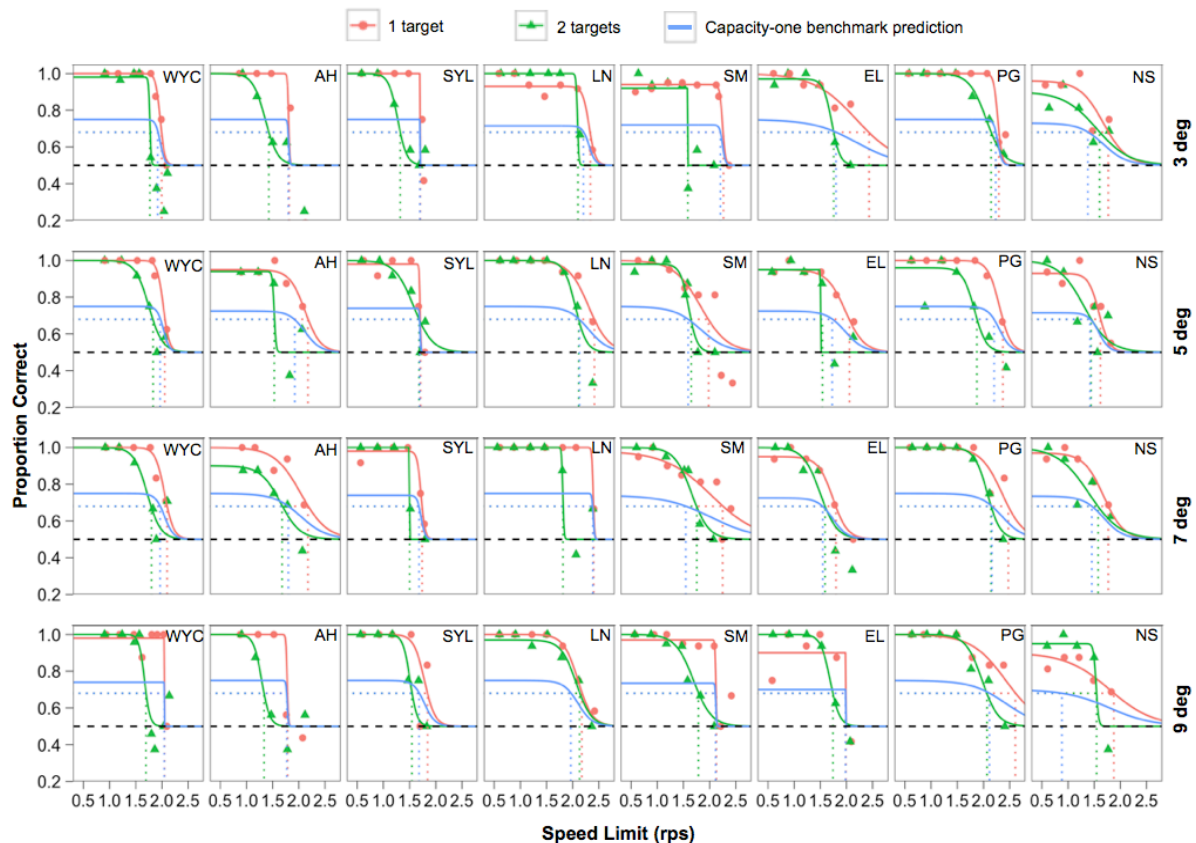


**Figure 3.8. Display of Experiment 7**

In Experiment 7, two pairs of blobs were presented in each condition. Each blob moved along a circular trajectory (dotted lines) and was confined to one quadrant. They were presented in one of four different separation conditions: Largest (9 deg), Large (7 deg), Small (5 deg), and Smallest (3 deg) separation. A blob from one or both pairs was designated as targets.

### 3.5.2 Results and Discussion

The data and associated psychometric plots for each of the seven participants in all conditions are shown in Figure 3.9. For every participant, the speed limit (68% threshold) for tracking one target (red points and curve) is better than for tracking two targets (green points and curve), which is similar to Experiment 4.



**Figure 3.9. Individuals' performance in Experiment 7**

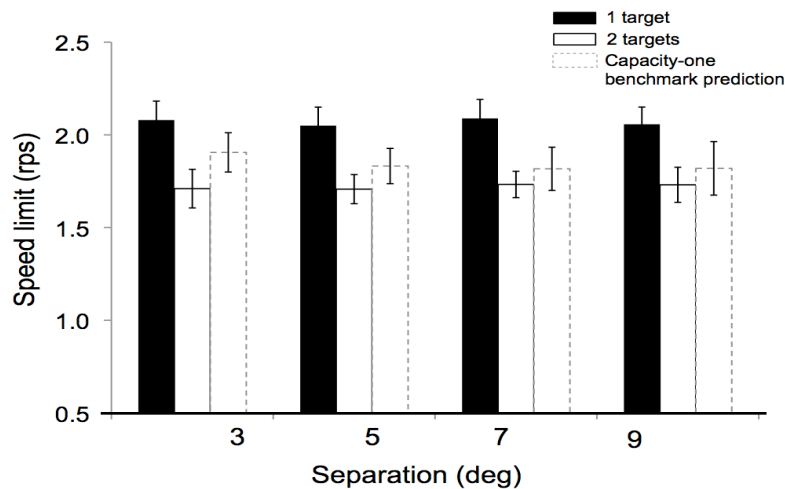
For each participant in Experiment 7, proportion correct is shown for each speed, in the one-target (red curve) and two-target (green curve) conditions. Also shown is the prediction for the two-target condition (blue curve) if the participant had a capacity limit of one target. Dotted lines show the 68% thresholds.

Figure 3.10 shows the average speed limits for tracking one (black bars) and two targets (white bars) across four different separation conditions. The capacity-one benchmark (dashed bars) provides some perspective on the speed limit decrement, showing what would have occurred in the two-target condition if participants could only track one target.

The observed speed limits were similar regardless of separation, contrary to the predictions of the spatial interference theory of Franconeri (2013). A repeated-measures

ANOVA with target number and separation as factors revealed no significant effect of separation,  $F(3, 21) = 0.108$ ,  $p = 0.954$ , partial  $\eta^2 = 0.015$ , and no significant interaction of separation and number of targets, thus  $F(3, 21) = 0.078$ ,  $p = 0.971$ , partial  $\eta^2 = 0.011$ . Spatial interference theory predicted that the speed limit for tracking two targets should have declined as the distance between targets decreased, especially in the two-target condition.

To complement the ANOVA analyses reported above, a regression analysis of the effect of separation on speed limit was performed. The slopes of the regressions were close to zero and not statistically significant. According to a simple linear regression, for 2 targets from 3 to 9 degrees,  $b = 0.004$ ,  $r^2 = 0.001$ ,  $t(30) = 0.205$ ,  $p = 0.839$ , 95% confidence interval for  $b = -0.035 \sim 0.043$ . For 1 target,  $b = 0.001$ ,  $r^2 = 0$ ,  $t(30) = -0.041$ ,  $p = 0.968$ , 95% confidence interval for  $b = -0.045 \sim 0.043$ .



**Figure 3.10. Averaged Speed Limits in Experiment 7**

The mean speed limits (68% thresholds) for tracking one (black bars) and tracking two (white bars) targets with four different separations are noted here. The speed limit for tracking two targets is substantially worse than the speed limit for tracking one. The dashed bars show the predicted two-target speed limit by a capacity-one benchmark. Error bars show one standard error across 8 participants.

Speed limits were much poorer for the two-target condition ( $M = 1.72$  rps) than the one-target condition ( $M = 2.07$  rps),  $F(1, 7) = 87.3$ ,  $p < 0.001$ , partial  $\eta^2 = 0.926$ . This decrement, together with the evident absence of significant spatial interference between the targets, supports the resource theory. Resource theory proposes that the cost of tracking

additional targets within one hemifield is due specifically to dividing a hemisphere-specific resource among the targets.

The capacity-one benchmark makes predictions for the speed limit for tracking two targets based on the performance of the one-target condition, under the assumption that participants can track only one target and have to guess on the half of trials in which they track the un-queried target. For slow speeds, participants do much better than the benchmark performance, indicating that they can track more than one target at slow speeds. At fast speeds however performance becomes more similar to the benchmark performance, raising the possibility that participants can only track one target at high speeds. Specifically, the measured speed limit (1.72 rps) was similar to that predicted by the capacity-one benchmark (1.84 rps),  $F(1, 7) = 4.267$ ,  $p = 0.078$ , partial  $\eta^2 = 0.379$ . The (non-significant) trend is for performance to be even worse than the capacity-one benchmark. One possible explanation is that at high speeds, participants can only track one target, but by attempting to track two they fail on both more often than they would have if they simply ignored the second target.

Table 3.1 reports the values of the “lapse rate” parameter in our psychometric function fit. The “lapse rate” term from psychophysics conveys that this includes complete lapses on the part of the participant, such as hitting the wrong key, which should differ little if at all across conditions. Other differences in difficulty across the conditions that are unrelated to speed would also yield differences in lapse rate, which was our interest here. Reassuringly, we found little to no change in lapse rate across the four distinct separations or for two targets versus one target (Table 3.1). A repeated-measures ANOVA with target number and separation as factors indicated the effects of number of targets ( $F(1, 7) = 0.537$ ,  $p = 0.488$ , partial  $\eta^2 = 0.071$ ) and separation ( $F(3, 21) = 0.411$ ,  $p = 0.747$ , partial  $\eta^2 = 0.055$ ) were not significant, and neither was their interaction ( $F(3, 21) = 0.73$ ,  $p = 0.546$ , partial  $\eta^2 = 0.094$ ).

**Table 3.1. Estimated lapse rates for different separations and targets in Experiment 7**

| Separation (deg) | 1 Target | 2 Targets |
|------------------|----------|-----------|
| 3                | .02±.03  | .03±.04   |
| 5                | .02±.03  | .02±.03   |
| 7                | .02±.02  | .01±.04   |
| 9                | .03±.04  | .01±.02   |

*Note.* Lapse rates ± Standard error across participants

Pelli and Tillman (2008) validated Bouma's law (Bouma, 1970) which states that for objects arrayed radially, spatial crowding for target identification occurs when distractors are separated from the target by less than half of target's eccentricity. According to this, for the smallest (3 deg) separation condition, the speed limit should be lower than other conditions because the separation is less than half of the target's mean eccentricity (the eccentricity of the centres of the trajectories was 8.5 deg). However, the speed limits across the four separation conditions were the same. There are a number of possible explanations for this.

One explanation is that the crowding zone for target tracking might be smaller than the zone for target identification. This explanation could be supported by the fact that observers can successfully track multiple moving targets without identifying targets (Pylyshyn, 2004). To date, the critical spacing related to eccentricity for attentive tracking is uncertain (Intriligator & Cavanagh, 2001). Intriligator and Cavanagh (2001) only demonstrated the critical spacing related to eccentricity for selecting targets. According to Intriligator and Cavanagh (2001), the critical spacing of the crowding effect for the target selection is less than 2 deg for our display of 8.5 deg of eccentricity. Thus, the future work should investigate the crowding effect on speed limit with the condition that the separation is less than 2 deg.

Another possible explanation is that tracking performance is robust with regard to the momentary difficulties of attentional selection. In this display, the blobs move in a circular trajectory. When the targets and distractors pass closely by each other, participants might confuse the two. But after this close encounter, participants might predict targets' next location according to their trajectory and thus be able to recover the target. This could explain

why we were unable to find an effect of separation on tracking accuracy in our experiment. Possibly, a different sort of tracking task, for example with more frequent changes in direction, would yield an effect of separation. However the important point for the interference vs. resource theory debate is that even with the present type of tracking display that does not exhibit a separation effect, performance is much worse with two targets, validating resource theory.

### **3.6 Discussion of Experiments 4-7**

These results provide support for the theory that a hemisphere-specific resource mediates tracking with excluding the confounding factor of spatial interference.

#### **3.6.1 Hemisphere-Specific Resource Theory**

Previous work has found evidence that tasks with demands on attentional selection show strong benefits on bilateral presentations, relative to unilateral presentations (Chakravarthi & Cavanagh, 2009; Reardon, Kelly, & Matthews, 2009). For example, Reardon et al. (2009) found that discriminating the orientation of two Gabor targets were better when the targets were presented bilaterally, but only if distracters were also presented.

For the task of tracking moving targets, Alvarez and Cavanagh (2005) found a very large advantage for bilateral presentations. However, they used objects moving at slow speeds and thus did not determine whether the benefit extended to the speed limit on tracking. The results of our Experiments 4, 5 and 6 provide the first evidence that bilateral presentations yield a higher tracking speed limit than unilateral presentations.

The bilateral presentation advantage on the tracking speed limit that our findings showed might support that there are two hemisphere-specific attentional tracking resources. In Experiment 4, speed limits for tracking one target were all around 1.7 rps whether the rotating doublets were aligned bilaterally or unilaterally. When increasing the number of targets from one to two, the decrement of speed limit was significantly greater as two rotating



doublets were presented within the same unilateral hemifield (0.27 rps), comparing to the bilateral hemifield arrangement (0.07 rps). It indicates that one hemisphere-specific resource can support observers to track one target moving within one hemifield up to 1.7rps. But the cost of adding another target is much larger in the same hemifield than in the opposite hemifield because two hemisphere-specific resources are independent.

Increasing the tracking load from two to four targets, Experiments 5 and 6 showed that the speed limit for tracking four targets was substantially lower than for tracking two targets bilaterally but was similar to that for tracking two targets unilaterally. Previous studies also found that tracking four targets in separated visual hemifields had little or no cost over tracking two targets within a single hemifield (Alvarez & Cavanagh, 2005; Battelli et al., 2009). Our experiments show that these results hold even when the objects are widely separated to avoid spatial interference and the total distance travelled by the blobs is held constant across trials. Holding travel distance constant was done to avoid a possible increase in spatial interactions with speed (Franconeri et al., 2010).

The similarity of the observed speed limits to the capacity-one benchmark limits is consistent with a linear resource-versus-performance function. It indicates that for tracking two targets within one single hemifield, the empirical performance is equivalent to what would occur if participants gave up on one target and focused all of the resource on the other target, as well as 50% of resource was not enough to track each fast-moving target. The capacity-one benchmark limits for the four-target condition were calculated using the two-target bilateral data in Experiments 5 and 6, which similar to using the one-target data to predict the capacity-one benchmark limit for the two-target unilateral condition in Experiment 4. Indeed, the actual performance non-significantly fell below the benchmark when tracking two targets within one hemifield, suggesting that the true resource-versus-performance function falls below the linear function. In other words, for fast targets, splitting

the resource in two may yield performance that is worse than halfway toward chance from one-target level. For example, more than half the resource may be required to have any tracking success with fast targets, and therefore if the participants try to track both in each hemifield, they will fail and have to guess regarding both, yielding performance even worse than the capacity-one benchmark limit.

The capacity-one benchmark limits provide a useful way for putting any load effects in perspective. For previous literature, the lack of such a benchmark makes it unclear whether a particular effect size is large enough to be consistent with the theory that the resource was all used, because no prediction (not even of a lower bound) was made. For example, a trend of a decrement in performance is sometimes observed when adding targets to the opposite hemifield (e.g. Experiment 1 and 3 of Alvarez & Cavanagh, 2005). Without a comparison like the capacity-one benchmark limit as well as a linear resource-versus-performance function, one is left unsure how much resource deployed to targets with the size of such decrements.

### **3.6.2 Excluding the Confound from Spatial Interference**

Some researchers might argue that the bilateral presentation advantage on speed limits we found was caused by the substantially stronger spatial interference between targets and distractors (Chakravarthi & Cavanagh, 2009; Liu et al., 2009) or between targets (Franconeri, 2013) when stimuli were presented within one single hemifield than across two hemifields.

The unique design of our paradigms is able to address the concerns of spatial interference between targets and distractors, or between targets. Firstly, the shortest spacing between targets and distractors in Experiments 4-6 is larger than the crowding zone that is predicted by the results of Intriligator and Cavanagh (2001) and even larger than that predicted by the Bouma's law. Thus, the worse performance with additional targets caused by the poor spatial resolution is avoided.

Furthermore, spatial interference between targets is also avoided by the configuration of the motion of targets and distractors. Each target always moves with another distractor within one of four quadrants. Our Experiment 7 measured the tracking speed limit by varying separations between two targets in separate quadrants within a hemifield. Speed limits for tracking one and two targets were not significantly different across four separation conditions from small to large. This provides empirical evidence against the Franconeri (2013)'s theory that the across-hemifield advantage on tracking performance results from a lack of spatial interference across the vertical midline, with long-range spatial interference constraining performance within a hemifield.

### **3.6.3 Tracking Resource is not Completely Hemisphere-Specific**

The tracking resource might be largely (but not entirely) hemisphere-specific. The first claim (that the resource is largely hemisphere-specific) is consistent with our primary measure of the speed limit cost for adding targets to the same or the opposite hemifield. Adding targets to the same hemifield yielded a much larger cost than adding targets to the opposite hemifield.

Nevertheless, the tracking resource may not be 100% hemisphere-specific. If the tracking resource were completely hemisphere-specific, the speed limit for tracking one target should be equal with that for tracking two targets in different visual hemifields. But in Experiment 4, five out of the eight participants had a statistically significantly higher speed limit when tracking one target than with tracking two targets, as revealed in Pair-t test,  $t(4) = 5.013$ ,  $p = 0.007$ . A non-significant trend for a cost of opposite-hemifield targets was also found in Experiments 5 and 6 as well as in both relevant experiments of Alvarez and Cavanagh (2005). In the case of an experiment conducted by Hudson, Howe, and Little (2012), the reduction in accuracy associated with adding targets in the opposite hemifield reached statistical significance (in their Experiment 4).

Two possible explanations for the resource not being entirely hemisphere-specific are suggested here. Firstly, in addition to two hemisphere-specific resources, there might be a global resource that can allocate resource to both hemifields. According to this hemisphere-specific plus global resource model, in the one-target condition, the speed limit benefits from the entire global resource plus the corresponding hemisphere-specific resource. In the bilateral two-target condition the speed limit is lower, because each of two targets receives its own hemisphere-specific resource plus only half the global resource. For example, for the bilateral arrangement in Experiment 4, the speed limit for tracking one target (1.7 rps) may have been (non-significantly) higher than tracking two targets (1.64 rps) owing to support from a global resource pool. Similar results were found in Experiment 5, tracking two targets in the unilateral hemifield (1.56 rps) has non-significantly higher speed limits than tracking four targets (1.52 rps), in which each hemifield includes two targets.

An alternative possible explanation is that the interhemispheric resource sharing (Maertens & Pollmann, 2005) benefits the speed limit for tracking one target. Maertens and Pollmann (2005) proposed that when two visual stimuli are presented in the left visual hemifield (LVF), first the right hemisphere (RH) processes the stimuli on its own. If the stimuli were complex enough to exhaust the RH resource, it is necessary to activate interhemispheric communication to share the resource from the LH. When it comes to Experiment 4, after increased speed completely depletes one single hemisphere-specific resource, if speed is further increased, the interhemispheric communication might be activated to share a part of resource from the other hemisphere-specific resource. Therefore, the speed limit for tracking one target is slightly higher than tracking two targets across hemifields.

### **3.7 Conclusion of Chapter 3**

In the first three experiments we demonstrated that the large cost on tracking speed limit for additional targets is largely hemisphere-specific. This hemisphere-specific effect is not caused by spatial interference between targets or between targets and distractors. There is a large speed limit cost when adding targets within the same hemifield but little or no speed limit cost when adding targets in the opposite hemifield, under the situation of equating the total distance that object travelled and utilizing wide separation between targets and distractors. The last experiment excluded the concern of a long-range spatial interference between targets on this hemisphere-specific effect.

## Chapter 4 : Differential Tracking Resource Allocation

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### 4.1 Introduction of Chapter 4

In previous chapters (2 and 3) we reported that, when spatial interference was avoided by using widely-spaced targets or equating the distance that objects travel across speeds, the speed limit nonetheless is worse when more targets must be tracked. These results support the hypothesis that a limited mental resource is involved in attentive tracking rather than just spatial interference.

This resource may comprise discrete pointers (sometimes called “slots”) that are assigned to the targets (Horowitz & Cohen, 2010; Pylyshyn & Storm, 1988) or a continuous pool of mental resource that is divided among the targets (Alvarez & Franconeri, 2007). An extreme variant of the slot theory posits that only one slot or spotlight is available, and it must be rapidly switched among targets for tracking to succeed (Tripathy & Howard, 2012; Tripathy et al., 2011).

The purpose of the present chapter is not to decide between these various competing resource theories, but rather to address an issue common to all of them. This is the question of whether different targets, presented simultaneously, can be allocated different amounts of the resource. For example, if the resource comprises four discrete tracking slots and two targets are presented, perhaps three slots can be devoted to the more-demanding target, with just one slot devoted to the less-demanding target. If the resource is instead a continuously divisible pool, then the more-demanding target might be allocated 75% of the resource and the less-demanding target only 25%. If the resource is instead a unitary focus of attention that is time-shared among the targets, it might visit the more-demanding target more often. In summary, a flexible resource may be differentially allocated among targets according to their demands, rather than split evenly between them.

#### **4.1.1 Variable Resource Allocation**

Although several studies have found evidence for an attentional-resource component to tracking, there is little evidence available regarding the possibility of differential resource allocation. For example, Tombu and Seiffert (2008) found evidence that tracking depends on an attentional resource that is also required when performing auditory tone discrimination. They also found evidence that tracking demands more of this resource when the targets are moving quickly. However, they did not investigate whether one can allocate more of the resource to one target (or one task) than to another.

Indirect support for differential resource allocation was found by Liu et al. (2005). In one of their experiments, half of the targets moved at 1 deg/s and the other half moved at 6 deg/s. They found that tracking accuracy was the same for both kinds of targets, even though one would expect that if both received equal resources, then accuracy would be poorer for the faster targets (Alvarez & Franconeri, 2007; Bettencourt & Somers, 2009). This was a null result, however, and one they did not discuss or follow up.

Experiments by Iordanescu, Grabowecky, and Suzuki (2009) also yielded some data that were interpreted as supporting differential resource allocation. Their observers viewed a number of moving discs and were asked to track a subset of them. All the discs were coloured and each target was a different colour. The objects moved about randomly and at the end of the trial, all the discs disappeared. Subsequently, the observers were asked to indicate the final location of a particular target (e.g. the red one). Observers were more accurate at indicating the final location of a target when the target was located near distractors. Iordanescu et al. (2009) suggested that this occurred because more resource is devoted to targets when they are near distractors because they are more demanding. However, two additional studies have failed to replicate this finding (Howard & Holcombe, 2008; Howard, Masom, & Holcombe, 2011). The reasons for the failure in replication are

unclear, but may have been because they did not directly manipulate proximity but rather relied on the random movements, so there may have been other display characteristics that differed when targets and distractors were nearby. On the other hand, Howard et al. (2011) purposely used a stimulus paradigm very similar to that employed by Iordanescu et al. (2009) and still failed to replicate the result of the Iordanescu et al. (2009).

Howe et al. (2010, Experiment 8) performed a more direct test of whether the tracking resource could be differentially reallocated between targets during tracking. In their displays, each object repeatedly paused so that it was moving for only half the tracking period. In the simultaneous condition, all the objects moved and paused simultaneously (i.e., synchronously). In the sequential condition, the objects were divided into two groups, each with an equal number of targets, and the two groups moved in alternation. When the objects in one group were moving, those in the other group were stationary. The rationale was that when an object was not moving, it would require less tracking resource (Alvarez & Franconeri, 2007; Bettencourt & Somers, 2009) and more resource could be allocated to the moving objects. Since fewer objects were moving at any one time in the sequential condition than in the simultaneous condition, it was expected that tracking performance would be greater in the sequential condition. Yet in fact, tracking performance was equal for the two conditions, suggesting that the tracking resource could not be dynamically reallocated between the targets. But to benefit performance in the Howe et al. (2010) study, any unequal distribution of resource would have to be reversed at the rate of the movement alternation. Perhaps participants *can* allocate resource unequally but cannot change this resource allocation rapidly. Our Experiment 8 will test whether the resource can be allocated with unequal amounts. Experiment 9 will test whether the resource can be successively reallocated between targets during the tracking period when the demands of the targets change.



#### **4.1.2 Tracking Resource Reallocation**

Consider the possibilities for dynamic allocation over the timeline of a tracking trial. The differential resource allocation might occur in the beginning of the tracking period and not change after that. Alternatively, this resource allocation between targets might change many times during the tracking period, because of removal of a target or changes in the difficulty of the targets, such as increases in a target's speed. For example, one target might receive half the resource during the first 0.5 sec and subsequently receive an additional quarter of the resource, while another target loses that quarter, after 0.5 sec tracking. Here we term this change in amount of resource during the tracking period (following the initial allocation)"resource reallocation".

Wolfe, Place, and Horowitz (2007) found observers' performance was unaffected by a requirement to reallocate resources to new targets during a tracking trial. Their experiments appear to be the first to demonstrate successful resource reallocation between targets over time. Three experimental conditions were used in their experiment: fixed, added and dynamic conditions. In the fixed condition, the target set remains the same set of four targets from the start of the trial. In the added condition, the trial starts with no targets and gradually the number of targets increases from one to four during the 20s tracking period. In the dynamic condition, the trial starts with no targets and first adds targets, after which targets are added or subtracted throughout the trial. The experiments yielded no significant difference in tracking performance among the three conditions, suggesting that the tracking resource can dynamically reallocate among new and old objects. However, as Wolfe et al. (2007) pointed out, performance in the three conditions cannot easily be quantitatively compared, because the average number of targets in the dynamic condition was fewer than the other two conditions, and in the fixed condition there were four targets for longer than in the other

conditions. Thus, this result indicates that the resource can be reallocated, but does not indicate whether or not it has a cost.

Ericson and Christensen (2012) addressed the problem from the study of the Wolfe et al. (2007) with a modified paradigm including six experimental conditions. These included four control conditions, in which observers were asked to track four or three targets during the 10s or 20s tracking period, an “added” condition, and a “subtracted” condition. In the added (3+) condition, observers were asked to track three targets at the start of trial, and after a 10 second tracking period, a new target was added. In the subtracted (4- ) condition, the trial started with tracking four targets and after 10s a target was removed.

Ericson and Christensen (2012) separately estimated the rate of missing targets for the first and second halves of the 20s trial. They predicted performance for the added (3+) condition using the performance of the 10s three-target condition and that of the second half of the 20s four-target condition. For example, the performance of the 10s three-target condition showed that observers lose an average of 0.3 targets during the 10s tracking period (i.e., capacity=2.7 targets). The performance of the second half of the 20s four-target condition was calculated by taking the capacity difference between the 10s (i.e., capacity=3.8 targets) and 20s (i.e., capacity=3.6 targets) four-target conditions, indicating the rate of missing targets during the last 10 s was 0.2/3.8. Thus, performance of the added (3+) condition was predicted by starting with performance of the 10s three-target condition (i.e., capacity=2.7 targets), adding one for the added target (i.e., capacity=3.7 targets, assuming the one is perfectly tracked for the first 10s), and then estimating the final capacity with the rate of missing targets of the second half of the 20s four-target condition (i.e., predicted capacity=3.51 targets). They also used the performance of the 10s four-target condition and that of the second half of the 20s three-target condition to predict the performance of the subtracted (4- ) condition. The logic of prediction for the subtracted condition is similar to,

but more complicated than, the added condition because the removed target may or may not be tracked at the time of removal (equation was shown in Ericson & Christensen, 2012).

Results showed that the actual and predicted performance was very similar (with no statistically significant difference), indicating that the addition or removal of a single target during the tracking period has no or little effect on tracking performance. It suggests that the tracking resource could be reallocated to targets throughout the trial depending on the change in target set, with no cost.

Both studies mentioned above were focused on the resource reallocation with change in number of targets. However, it is unknown whether any tracking resource can be reallocated between targets when target speeds change during the trial (presuming that more of the resource can be given to targets with higher speed than to those with lower speed, which is tested in Experiment 8).

The reallocation of resources in the Wolfe et al. (2007) study was required every 2 s on average- this was the average interval between changes in the target set. These results indicate that observers can reallocate the tracking resource between targets at a slow rate of 2 sec per change, while the Ericson and Christensen (2012) study was less demanding, with a target added or subtracted only once during the 20s tracking period. However, observers might not be as capable of resource reallocation at higher rates, such as when targets change speed continuously. Our Experiment 9 is designed to investigate this.

Having found in Chapter 3 that a hemisphere-specific resource determines the tracking speed limits, our Experiment 8 tested the possibility of differential allocation of the resource, with more resource allocated to the faster of two targets. In one condition, both targets moved at the same speed whereas in the other condition they moved at different speeds. The results indicate that observers' speed limit for one target is higher when the other target is moving more slowly. This suggests that when a target moves slowly, less resource is

needed to track it; hence, more resource is available to track the other target. This thereby allows the target to be tracked at a higher speed.

In Experiment 9, we investigated whether this resource allocation could be varied in accordance with a change in speed of the two targets during the tracking period. The results indicate that the differential resource allocation between targets with different speeds might only occur in the target-cueing period, and this resource allocation does not change during the tracking period even there is only one change in speed.

#### **4.2 Experiment 8: Resource Allocation between Targets of Different Speeds**

Under the umbrella of resource theory, different amounts of resource might be allocated to different targets in a demand-based manner. This possibility was tested in Experiment 8 by comparing the speed limit at which observers could track a particular blob (the “critical target”) under two conditions, both of which required the observer to track two targets (a critical and a non-critical target). In the “other-slow” condition the non-critical target moved at a slow speed of 0.5 rps whereas in the “same-speed” condition the non-critical target moved at the same speed as the critical target.

We reasoned that because in the other-slow condition the non-critical target was slower than the critical target, less resource would be needed to track it (Alvarez & Franconeri, 2007; Bettencourt & Somers, 2009). This should leave more resource for the critical first target, allowing it to be tracked at a faster speed, provided that resource can be allocated unequally. Because the resource pools operate independently for the left and right visual hemifields (Alvarez & Cavanagh, 2005), we predicted that an improved speed limit for the other-slow condition would only occur for the unilateral arrangement (both targets to the left or to the right of fixation), not the bilateral arrangement (the targets in different hemifields).

## **4.2.1 Method**

### **4.2.1.1 Participants**

Seven participants (six male, one female, 27-32 years of age) who reported normal or corrected-to-normal vision agreed to participate in the protocol, which was approved by the University of Sydney's ethics committee. All had extensive experience fixating in laboratory experiments.

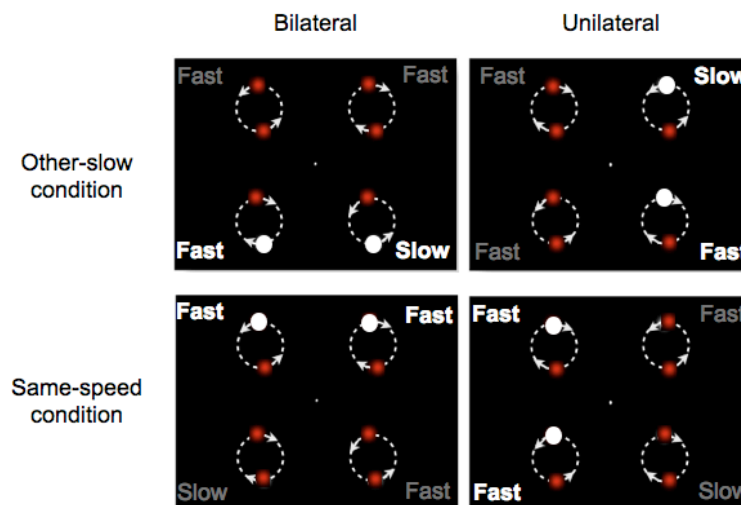
### **4.2.1.2 Stimuli**

Stimuli were displayed in a dimly lit room on a 21 in. SONY Multiscan G520 CRT monitor (1,024 x 768 resolution) with a refresh rate of 120 Hz controlled by a MacBook running a Python program that used PsychoPy software (Peirce, 2007). Viewing distance was 57cm, with a chin rest and forehead support to avoid subject head movement.

Eight red blobs (evoked by the red gun only, with Gaussian intensity profiles; visible diameter 1 deg; peak luminance 20 cd/m<sup>2</sup>) and a white fixation dot (radius: 0.1 deg, luminance: 167 cd/m<sup>2</sup>) were presented against a black background (41°x31°, luminance: 0.02 cd/m<sup>2</sup>). The spatial arrangement of the objects is schematized in Figure 4.1. Four pairs of blobs were presented in all conditions. Each pair moved on a circular trajectory that was centred in one of the four quadrants of the visual field. Each circular trajectory was centred on a point 6 deg from the vertical midline and 6 deg from the horizontal midline (representing one of the four quadrants). The radius of each trajectory was 2.5 deg, and because the two blobs on a trajectory were always diametrically opposed, the separation between them was always 5 deg. This separation is larger than the critical spacing within the crowding zone (4.25 deg), which is calculated as half of eccentricity (8.5 deg) of the centre of each circular trajectory. These distances should be large enough to avoid crowding among the objects (Intriligator & Cavanagh, 2001; Pelli & Tillman, 2008).

In Experiment 8, observers were always asked to track two targets, which were placed in either the same hemifield (unilateral arrangement) or opposite hemifields (bilateral arrangement). In the bilateral arrangement, in half the trials the targets were both above the fixation point and in the other half both targets were below the fixation point. In the unilateral arrangement, in half the trials the targets were both to the left of the fixation point, and in the other half both were to the right of the fixation point (Figure 4.1).

The main manipulation of this experiment was the difference between the targets' speeds. In the same-speed condition, the two targets moved with equal speeds, which varied across trials from 0.9 to 2.1 rps. In the other-slow condition, the critical target moved at a speed between 0.9 and 2.1 rps and the slow target always moved at 0.5 rps. At the end of the trial, one pair of blobs was indicated with a white line and the participants used the mouse to indicate which of the two blobs was the target. Both targets were equally likely to be queried.



**Figure 4.1. Display of Experiment 8**

In Experiment 8, four pairs of red Gaussian blobs were presented in each condition. Each pair moved along a circular trajectory (dotted lines) and was centred in one quadrant. A blob from each of two pairs was designated as targets by being cued in white. For the bilateral arrangement, the targets were both above or both below fixation whereas for the unilateral arrangement, both targets were to the left or to the right. In the other-slow condition, one target always moved slowly (0.5 rps). In the same-speed condition, the two targets moved at the same speed (which varied across trials).

#### **4.2.1.3 Procedure**

Observers were told to maintain fixation on the white dot at the display centre. The trial started with the two target blobs presented in white and the remaining blobs in red. All four pairs of blobs revolved in the same direction (clockwise or counter clockwise) at the beginning of the trial and their initial angles about the circular trajectory were set randomly on each trial. After the 0.7s target-cuing period, all blobs were red. During the tracking period, the blobs occasionally reversed direction to prevent participants from predicting the final target positions from their initial positions and speeds. Each pair of blobs was independently assigned a series of reversal times, which succeeded each other at random intervals between 1.2 and 2 s. For this experiment's 3 to 3.8 s tracking interval, this resulted in 2 or 3 reversals.

At the end of a trial, one pair of blobs was indicated with a white line (see Figure 3.2 in Chapter 3) and participants were used the mouse to indicate which was the target.

The slower target always moved at 0.5 rps. Each observer participated in 128 trials at each of the five speeds for the faster targets, with the speeds for each condition and person chosen on the basis of piloting, ranging from 0.9 to 2.1 rps. Observers were presented with 640 experimental trials in total, divided into four sessions. Each participant did no more than two sessions a day and had a minimum break between sessions of 5 minutes.

#### **4.2.1.4 Data Analysis**

Plots of speed versus proportion correct were fit by a logistic regression that spanned from chance (50% accuracy) to a ceiling level of performance. The ceiling performance corresponds to the lapse rate, which in the fitting procedure was allowed to vary from 0% to 10% to get the best estimate. This estimated lapse rate for each condition is reported in the results section. We define the “speed limit” as the speed at which performance is estimated

by the regression to fall to 68% correct. The regression was fit separately for each participant and condition to calculate the speed limits.

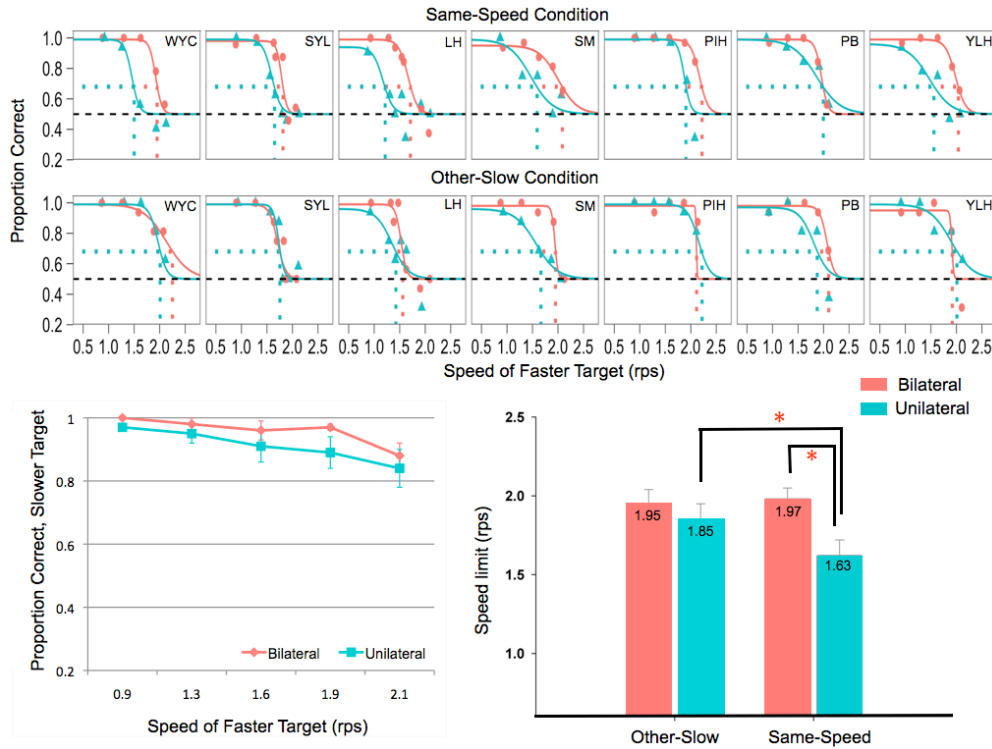
#### 4.2.2 Results and Discussion

For each participant, the data and associated psychometric curves are shown in Figure 4.2 for the same-speed vs. other-slow conditions and the unilateral vs. bilateral arrangements. When the participants tracked two moving targets with equal and fast speeds (same-speed condition), performance for the bilateral arrangement (red curve) was better than for the unilateral arrangement (blue curve). A paired t-test for the same-speed condition found that across the seven subjects, the speed limit of the bilateral arrangement (1.97 rps) was significantly higher than that of the unilateral arrangement (1.63 rps),  $t(6) = 4.743$ ,  $p = 0.003$ , Cohen's  $d = 1.887$ , bottom right panel of Figure 4.2, further supporting the hemisphere-specific resource theory.

In the unilateral arrangement, most of the participants had higher performance for the fast target when the second target moved slowly (other-slow condition) compared to when it moved at the same speed, paired t-test,  $t(6) = -2.649$ ,  $p = 0.038$ , Cohen's  $d = -1.005$ . This is the critical finding, supporting the theory that in the unilateral arrangement each target was allocated different portions of the hemifield-specific resource, depending on its speed.

The results of the bilateral arrangement suggest that tracking resources cannot be shared across the vertical hemifield boundary to the extent that they can within a hemifield—in the bilateral arrangement, there is no significant difference between the speed limit of the faster target for the same-speed condition and the other-slow condition,  $t(6) = 0.278$ ,  $p = 0.79$ , Cohen's  $d = 0.112$ . This difference between the unilateral and bilateral arrangements was confirmed by the significant interaction between hemifield arrangement and speed found in a repeated-measures ANOVA,  $F(1, 6) = 6.68$ ,  $p = 0.042$ , partial  $\eta^2 = 0.527$ .





**Figure 4.2. Results of Experiment 8**

**Top.** For each participant, proportion correct is shown for each speed in the two-target bilateral (red) and two-target unilateral (blue) arrangements. Top row shows performance in the same-speed condition, averaging across both targets. Bottom row shows the other-slow condition, for the faster critical target. Dotted lines show the speed limits (68% thresholds). **Bottom right.** Red bars show the speed limits for the bilateral arrangements in the same-speed and other-slow (faster target only) conditions. The blue bars show the speed limit for the unilateral arrangements in the same-speed and other-slow (faster target only) conditions. Error bars show one standard error across participants. Red stars indicate statistically significant differences,  $p < 0.05$ . **Bottom left panel.** Tracking accuracy for the slow target (mean across subjects) is shown for the other-slow condition, as a function of the speed of the fast target.

In order to understand in more detail how tracking performance was affected by the speed difference of the targets, the performance for tracking the slow target (in the other-slow condition) is plotted at the bottom left panel of Figure 4.2. It shows percentage correct for the slow target as a function of speed of the faster target.

For the slow target, a downward trend in tracking accuracy was observed as the speed of the fast target was increased. This was analysed by linear regression in the unilateral arrangement ( $b = -0.106$ ,  $r^2 = 0.161$ ,  $p = 0.017$ ) and in the bilateral arrangement ( $b = -0.058$ ,  $r^2 = 0.132$ ,  $p = 0.032$ ). The drop was significantly larger for the unilateral arrangement than the bilateral arrangement according to a paired t-test comparing the slopes of the two conditions,  $t(6) = 2.512$ ,  $p = 0.046$ , Cohen's  $d = 1.105$ . This was not significant however in the alternative

analysis of a repeated-measures ANOVA, where it would have manifest as an interaction between speed and hemifield arrangement,  $F(4, 24) = 0.898, p = 0.481$ , partial  $\eta^2 = 0.13$ . The ANOVA did show a significant speed effect,  $F(4, 24) = 3.361, p = 0.026$ , partial  $\eta^2 = 0.359$ , and a marginally significant hemifield arrangement effect,  $F(1, 6) = 5.161, p = 0.064$ , partial  $\eta^2 = 0.462$ . A significant decrease in performance regardless of the hemifield of the faster target would suggest that the resource is not 100% hemisphere-specific. More data would be needed to be confident of this.

Returning to the main results of speed limits, the lower speed limits in the unilateral arrangement do not reflect a general greater difficulty irrespective of relative blob speed. One possible explanation is that a general difficulty factor might cause the psychometric function to saturate at a lower ceiling in the unilateral condition. This is not apparent in the plots, and we confirmed the lack of any significant effect by examining the lapse rates of the fits. The lapse rate sets the ceiling on performance. A repeated-measures ANOVA showed no significant differences in lapse rates between the unilateral (0.01) and bilateral (0.02) conditions ( $F(1, 6) = 0.625, p = 0.459$ , partial  $\eta^2 = 0.094$ ), and between the same-speed (0.02) and other-slow (0.02) conditions ( $F(1, 6) = 0.104, p = 0.758$ , partial  $\eta^2 = 0.017$ ), and no significant interaction between the two hemifield arrangements and speed conditions ( $F(1, 6) = 0.057, p = 0.819$ , partial  $\eta^2 = 0.009$ ). Any speed-invariant difficulty difference was non-existent or too small to be detected.

#### **4.3 Experiment 9: Inefficient Resource Reallocation between Targets.**

The hemisphere-specific resource can be differentially allocated to targets differing in speeds (Experiment 8). The speed limit was substantially higher for a target if the other target was slow than if the other target was fast (provided both targets are in the same hemifield).

Previous studies showed that the mental resource can be reallocated when targets appear or disappear during the tracking period, with little to no effect on tracking

performance (Ericson & Christensen, 2012; Wolfe et al., 2007). Besides changes in the target set, tracking resource might be reallocated according to changes in target speed during the trial. The previous chapter found that more resource is allocated to the fast target than the slow one. Thus, if we increase the speed of one target and decrease the speed of the other target during the trial, the resource might be reallocated from the speed-decreasing target to the speed-increasing target. The purpose of this experiment is to investigate whether change in target speed during the trial influences the tracking resource reallocation.

Observers might be capable of reallocating resource between targets at a slow rate of 2 sec per change (Ericson & Christensen, 2012; Wolfe et al., 2007), but unable to reallocate resource at high change rate. It is unknown whether tracking performance drops when we increase the rate of resource reallocation between targets. With a shorter duration for each change (e.g. 1 sec per change), the speed of attention reallocation between targets might be not fast enough to deal with an increase in the speed of the target, leading to a failure of tracking. Comparing with the previous studies using the change rate of 2 sec per change (Ericson & Christensen, 2012; Wolfe et al., 2007), Experiment 9 investigates whether tracking performance worsens if we set the change rate is 0.1 sec per change (0.1 rps speed change per 0.1 sec).

To investigate whether change in target speed during the trial influences the tracking resource reallocation, five experiment conditions were used in this experiment and described in the following sections (Table 4.1).

In the two-target speed switch (TSS) condition, observers tracked one initially-slow and one initially-fast target at the start of the trial. During the tracking period, the initially-slow target gradually increased its speed until it was equal to that of the initially-fast target, and the initially-fast target gradually decreased speed to be equal to that of the initially-slow target. Under this condition, some tracking resource should be reallocated from the initially-

fast to the initially-slow target, based on the theory of the fast moving target consuming more resource than the slow one.

**Table 4.1. The five conditions of Experiment 9**

| Condition                       | Description  |
|---------------------------------|--|
| Two-Target Speed Switch (TSS)   | At the start of the trial, one target moves fast and the other slow. The initially-slow target increases speed gradually to be equal to the speed of the initially-fast target whereas the initially-fast target gradually slows to be equal to the speed of the initially-slow target (switching the speeds between two targets). |
| One-Target Speed Changed (TSC)  | At the start of the trial, one target moves fast and the other slow. During the trial, the initially-slow target increases speed gradually to be equal to the speed of the initially-fast target.  |
| Same-Speed Unchanged (SSU)      | Two targets with equal speeds and no speed changes.  |
| Different-Speed Unchanged (DSU) | One fast-moving target and one slow-moving target with no speed changes  |
| One Target (ONE)                | Observers track only one target throughout the trial and its speed does not change during the trial.   |

Compared to a target that moves at a constant fast speed throughout the trial, any observed improvement in performance for the initial-slow target in the TSS condition might be a result of its shorter duration moving at the fast speed. To exclude this possibility we designed the one-target speed changed (TSC) condition as a control condition. In the TSC condition, the trial started like the TSS condition, but only the initially-slow target changed speed. Its speed increased gradually to be equal to the speed of the fast target, and the speed of the fast target was constant throughout the trial. It is hypothesized that the speed limit for the initially-slow target in the TSS condition should be significantly higher than the equivalent target's speed limit in the TSC condition. According to the assumption of resource reallocation depending on the change in target speed, resource is reallocated from the initially-fast target to the initially-slow target in the TSS condition but not in the TSC condition.

To confirm the result of Experiment 8 that resource can be differentially allocated to two targets of different speeds, we replicated two of the Experiment 8 conditions. Here, we called the “other-slow” condition from Experiment 8 as the “different-speed unchanged (DSU)” condition, and the “same-speed” condition from Experiment 8 as the “same-speed

unchanged (SSU)” condition. A final condition provided a baseline speed limit for tracking only one target (one target condition; ONE).

### **4.3.1 Method**

#### **4.3.1.1 Participants**

Nine participants (six male, three female, 22-37 years of age) who reported normal or corrected-to- normal vision agreed to participate in the protocol, which was approved by the ethics committee of the University of Sydney. All had extensive experience fixating in laboratory experiments.

#### **4.3.1.2 Stimuli**

With the following exceptions, the apparatus and stimuli employed were identical to those of Experiment 8. Observers were instructed to track simultaneously one or two targets within one single hemifield. In half the trials the targets were both to the left of the fixation point, and in the other half both were to the right of the fixation point.

The primary manipulations were 1) whether the speeds of these two targets were different or not and 2) whether the speed increased or not during the tracking period. In the same-speed unchanged (SSU) condition, the two targets moved with equal speeds throughout the trial, which varied across trials from 0.6 to 2.4 rps. In the different-speed unchanged (DSU) condition, the slow target always moved at 0.5 rps and the fast target moved at a speed between 0.6 and 2.4 rps. In the one-target speed changed (TSC) condition, the speed of the two targets started as identical to the DSU condition. After a 0.5 second tracking period, the initially-slow target started to increase speed from 0.5 rps to the same speed as the fast target (e.g. from 0.5 to 1.8 rps) with a 1 revolution/sec<sup>2</sup> acceleration rate, and the fast target always moved at a constant speed during the trial. The two-target speed switch (TSS) condition was identical to the TSC condition except that the initially-fast target started to decrease speed to 0.5 rps with 1 revolution /sec<sup>2</sup> deceleration rate (e.g. from 1.8 to 0.5 rps) at the same moment

as the speed change of the initially-slow target (Figure 4.3). In addition to these two-target conditions described above, we also have a condition for tracking only one target, whose speed was set to a constant value between 0.6 to 2.4 rps (varying across trials). The quadrant that the target appeared in was counterbalanced across trials.

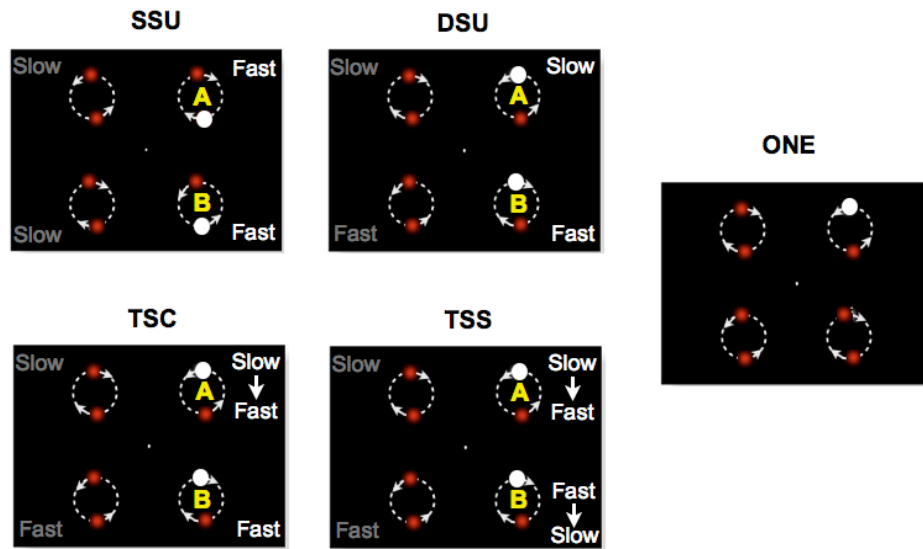
The total tracking interval was lengthened relative to Experiment 8 to between 4.0 and 4.8 s, in order to provide enough time for the targets to gradually change speeds. After a 0.7 s target-cuing period, the target blob became red (like the distractors) and each blob pair was independently assigned reversal times that succeeded each other at random intervals between 1.2 and 2 s. At the end of a trial, one pair of blobs was indicated with a white line and participants were prompted to use the mouse to indicate which was the target.

The testing speeds for each condition and person were chosen on the basis of piloting. Five testing speeds were used on different trials and presented in pseudorandom order and fully crossed with all experimental conditions. Each person participated in at least 480 trials of an experiment, which usually involved four sessions. Each participant did no more than two sessions a day and had a minimum break between sessions of 5 minutes.

#### **4.3.1.3 Data Analysis**

The data was analysed as in previous experiments, with speed limits (68% thresholds) extracted from the psychometric curve fit. In contrast to previous experiments, in this experiment we separately calculated the speed limit for each target within each hemifield rather than averaging the speed limits of two targets. Thus, we have different terms to represent each target in each condition with the initial speed of the target. In the TSC condition, the initially-slow target was termed as the “TSCS” and the fast target was termed as the “TSCF”. In the TSS condition, the initially-slow target was termed the “TSSS” and the initially-fast target was termed the “TSSF”. In the DSU condition, the fast target was termed

the “DSUF”. In the SSU condition, we averaged the speed limits of both targets because there are equal speeds throughout the trial.

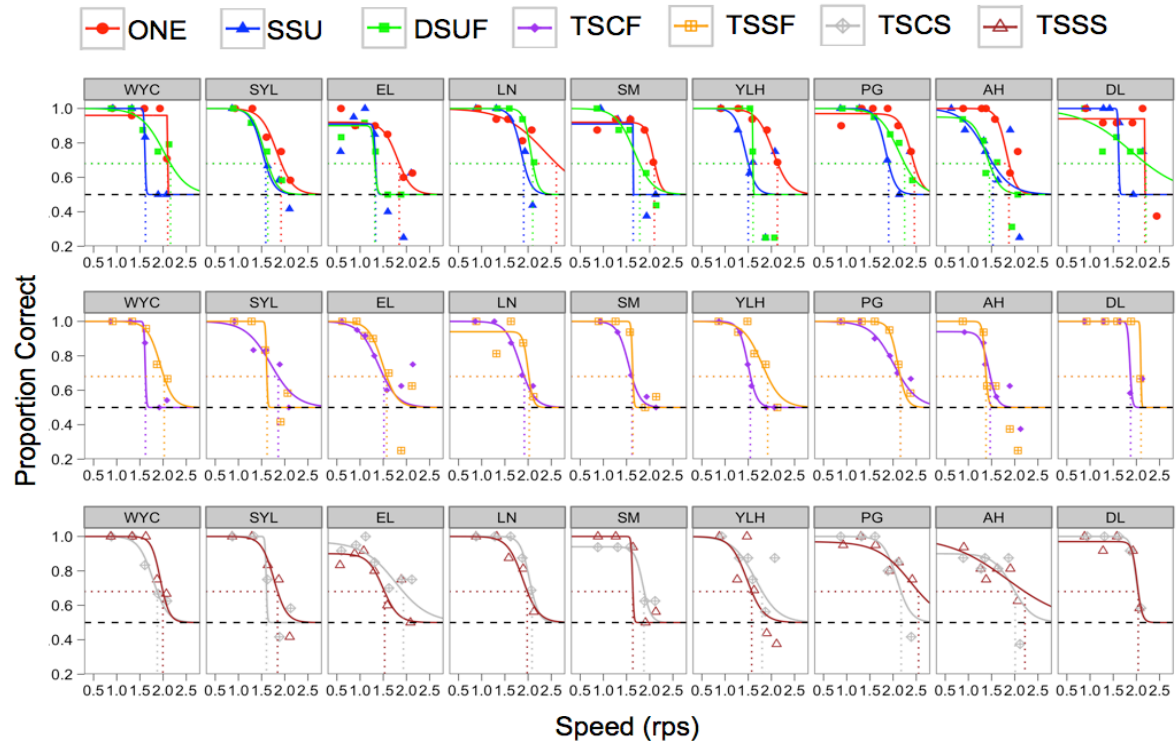


**Figure 4.3. Display of Experiment 9**

In Experiment 9, four pairs of red Gaussian blobs were presented in each condition. Each pair moved along a circular trajectory (dotted lines) and was centred in one quadrant. In the one-target (ONE) condition, a blob from one of four pairs was designated the target. In other conditions, a blob from each of two pairs was designated a target. The targets were only presented as a unilateral arrangement either right or left hemifield. In the same-speed unchanged (SSU) condition, the two targets moved at the same speed (which varied across trials from 0.6 to 2.4 rps based on a method of constant stimuli design). In the different-speed unchanged (DSU) condition, the slow target always moved at 0.5 rps and the fast target moved at a testing speed between 0.6 and 2.4 rps. In the one-target speed changed (TSC) condition, the speed of two targets started as identical to the DSU condition. After a 0.5 second tracking period, the initially-slow target started to increase speed from 0.5 rps to the same speed as the fast target (e.g. from 0.5 to 1.8 rps) with a 1 revolution/sec<sup>2</sup> acceleration rate, and the fast target always moved at the constant speed. The two-target speed switch (TSS) condition was identical to the TSC condition except that the initially-fast target started to decrease speed to 0.5 rps with a 1 revolution/sec<sup>2</sup> deceleration rate (e.g. from 1.8 to 0.5 rps) at the same moment as the speed change of the initially-slow target.

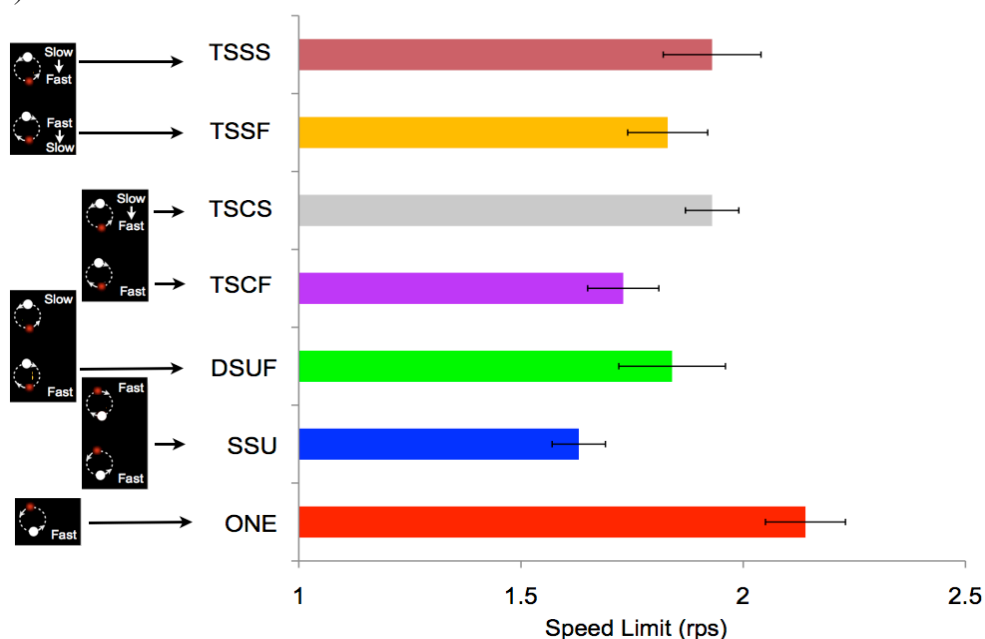
### 4.3.2 Results and Discussion

For each participant, the data and associated psychometric curves are shown in Figure 4.4 for all conditions in Experiment 9. Similar to previous experiments, within one hemifield performance for tracking one target (red curve) was better than for tracking two targets moving with equal speeds (blue curve), supporting the hemisphere-specific resource theory.



**Figure 4.4. Individuals' performance in Experiment 9**

The colour curves showed the tracking performance across speeds for all conditions. The top panel presented the performance for tracking one target (red curve; ONE), for tracking two targets with equal speeds (blue curve; SSU), and for tracking two targets with different speeds (green curve; DSUF). The middle and bottom panels presented the performance for tracking two targets with speed changing during the trial, and performance of the initially-fast targets was shown in the middle panel and performance of the initially-slow targets was shown at the bottom panel. In the middle panel, the purple curve showed the performance of the fast target, which did not change speed during the trial (TSCF) whereas the yellow curve showed the performance of the initially-fast target, which speed gradually decreased during the trial (TSSF). At the bottom panel, the grey curve showed the performance of the initially-slow target in the condition that was paired with a fast target without speed changing during the trial (TSCS) whereas the brown curve showed the performance of the initially-slow target in the condition that was paired with an initially-fast target with speed switching during the trial (TSSS).





**Figure 4.5. Speed limits in Experiment 9**

The coloured bars show the averaged speed limits across 9 participants for all conditions. Error bars show one standard error across participants. The speed limit for tracking one target (lower red bar; ONE) was significantly higher than for tracking two targets across all of the two-target conditions. The speed limit for tracking two targets moving with equal speeds (lower blue bar; SSU) was substantially lower than other two-target conditions that two targets moved with different speeds. Contrary to the resource reallocation prediction, the speed limit for the initial-slow target in the two-target speed switch condition (upper pink bar; TSSS) is not significantly different from that in the one-target speed changed condition (middle grey bar; TSCS).

The speed limits, averaged across participants, are shown for each target of each condition in Figure 4.5. Consistent with resource theory, the speed limit for tracking one target (2.14 rps) was significantly higher than for tracking two targets across all the two-target conditions. Paired t-tests applied to the comparison of each condition with the two-target condition yielded a  $p$ -value of 0.05 or less (SSU:  $t(8)=12.419$ , Cohen's  $d=5.18$ ; DSC1F:  $t(8)=6.606$ , Cohen's  $d=2.222$ ; TSCS:  $t(8)=2.934$ , Cohen's  $d=1.058$ ; DSC2F:  $t(8)=5.229$ , Cohen's  $d=1.753$ ; TSSS:  $t(8)=1.951$ , Cohen's  $d=0.662$ ; DSUF:  $t(8)=4.034$ , Cohen's  $d=1.461$ ).

Similar to Experiment 8, comparing the other-slow condition (different-speed unchanged, DSU) to the same-speed condition (same-speed unchanged, SSU), the speed limit for the fast target in DSU condition (1.84 rps) was substantially higher than in the SSU condition (1.63 rps), as revealed by a paired t-test ( $t(8)=-2.646$ ,  $p=0.029$ , Cohen's  $d=-1.203$ ). It indicates the one hemisphere-specific resource can differentially allocate to targets differing in speeds, with more resource allocated to the fast one than the slow one.

For the fast or initially-fast targets in the one-target speed change (TSC) and the two-target speed switching (TSS) conditions, the speed limit of both targets should be similar to the fast target in the DSU condition, because the differential resource allocation can benefit the tracking performance of the fast target. Indeed, a repeated-measures ANOVA showed no significant difference on speed limit among these three targets ( $F(1, 8)=1.655$ ,  $p=0.234$ , partial  $\eta^2=0.171$ ). In addition, the speed limits for targets in the SSU condition (1.63 rps) was substantially lower than these fast targets in the TSS (1.83 rps) condition and in the TSC

(1.73 rps) condition as revealed by a paired t-test (TSSF:  $t(8) = -2.761, p = 0.025$ , Cohen's  $d = -1.002$ ; TSCF:  $t(8) = -2.327, p = 0.048$ , Cohen's  $d = -0.827$ ). These statistical results suggest that the differential resource allocation at the start of the trial is maintained throughout the trial.

Contrary to the prediction of resource reallocation between targets that switch speeds, the speed limit for the initially-slow target in the TSC condition (TSCS, 1.93 rps) was not significantly lower than the initially-slow target in the TSS condition (TSSS, 1.93 rps), as revealed by a paired t-test ( $t(8) = 0.038, p = 0.97$ , Cohen's  $d = 0.015$ ). This suggests that participants might not be capable of reallocating attentional resource between targets differing in speeds at the 1 revolution/sec<sup>2</sup> acceleration/deceleration rate.

The reason why observers do not reallocate resource between two targets with switching speeds might be that humans have poor sensitivity to detection of speed change (McBeath, Shaffer, & Kaiser, 1995). Observers clearly detect the speed change when the range of changing speed is above 50% (Traschutz, Zinke, & Wegener, 2012). For our TSS condition, the range of changing speed is less than 25% for every change. Thus, observers might be delayed in detecting the speed change when the initially-slow target accelerates at 1 revolution/sec<sup>2</sup>, especially at high speeds. Attention reallocation must occur after humans detect the speed change, so that observers might start to shift their attention very late and lose the tracked target with the incorrect amount of resource allocated to it. Therefore, the delayed detection of the speed change can explain why observers did not reallocate resources from the initially-fast target to the initially-slow target. Future investigation should increase the speed change to facilitate its detection.

The tracking duration at fast speeds within a trial is also a determinant of the speed limit. The speed limit is substantially higher when the tracking duration at fast speeds is shorter. Compared to the speed limit for the SSU (1.63 rps), the shorter fast interval within a trial for the TSCS (1.93 rps), TSSS (1.93 rps), and TSSF (1.83 rps) yielded significantly

higher speed limits (TSCS:  $t(8) = -5.3, p = 0.001$ , Cohen's  $d = -1.77$ ; TSSS:  $t(8) = -3.628, p = 0.007$ , Cohen's  $d = -1.43$ ; TSSF:  $t(8) = -2.761, p = 0.025$ , Cohen's  $d = -1.002$ ).

#### **4.4 Discussion of Experiments 8-9**

These results provide new support for the theory that a hemisphere-specific resource mediates tracking, and that this resource can be differentially allocated to targets with different speeds. In the unilateral (same hemifield) arrangement, pairing a target with a slower target rather than one of the same speeds yielded better performance for the first target, presumably because slower targets are allocated less resource than faster targets. In addition, this differential resource allocation effect on speed limit might maintain throughout the trial even though the target speed changed during the tracking period. Alternatively, the reallocation may have occurred but may have required resources itself, imposing a cost that nullified any benefit in the circumstances of these trials. In other words, the resource reallocation due to change in target speed was inefficient at least at the 1 revolution/sec<sup>2</sup> acceleration/deceleration rate.

##### **4.4.1 Differential Allocation of the Hemisphere-Specific Resource**

Experiment 8 provided evidence that the resource can be differentially allocated to targets differing in speed, and that this effect was much bigger within hemifields than across hemifields, which further supports the hemisphere-specific theory. We found that a target could be tracked at a faster speed when the other target within the same hemifield was moving relatively slowly (Experiments 8 and 9). Across hemifields, that effect was not significant. For performance tracking the slow target however, there was a significant although small effect of the speed of the target in the opposite hemifield, suggesting that the resource is largely but not entirely hemisphere-specific.

The conclusion from the differential allocation evidence (Experiment 8)- that the resource is largely hemisphere-specific- is consistent with our previous measures of the speed

limit cost for adding targets to the same or the opposite hemifield in Chapter 3. Adding targets to the same hemifield yielded a much larger cost than adding targets to the opposite hemifield. In support of the notion that a small amount of resource can be shared across hemifields, a non-significant trend for a cost of opposite-hemifield targets was found in the experiments of Chapter 3 as well as in both relevant experiments of Alvarez and Cavanagh (2005). In an experiment conducted by Hudson et al. (2012), the reduction in accuracy associated with adding targets in the opposite hemifield reached statistical significance (their Experiment 4).

Although differential resource allocation was documented in our Experiment 8, the tracking resource might not be dynamically reallocated between the targets during the trial. The experiment 6 in Howe et al. (2010) showed that if observers were encouraged to serially track objects (dynamically reallocating resource in turn) by using very long durations of each pausing and movement phase, the performance with serial tracking was better than parallel tracking. This result suggests that it takes time to dynamically reallocate resource between targets.

Experiment 9 further investigated the possibility of resource reallocation by changing the speed of the targets during the tracking period. Results showed that after the first differential resource allocation to targets in the cueing period, observers tend to maintain this allocation to the initial target throughout the trial, or any reallocation is too costly to provide a benefit.

Why can humans efficiently reallocate tracking resource between targets when the target number changes (Ericson & Christensen, 2012; Wolfe et al., 2007) but not when the target speed changes during the trial? One possible explanation is that reallocating tracking resource takes time to complete. Both the studies that varied target number used relatively infrequent changes during the tracking period, with changes occurring every 1-2 sec in Wolfe

et al. (2007)'s experiments. Drew, Horowitz, Wolfe, and Vogel (2012) also showed observers were capable of deleting their current target set and acquiring new targets throughout the trial but it took around 0.5 sec to reallocation the attentional resource on each variation of target number. This resource reallocation for change in target number resembles pouring juice (resource) from one cup to the other in 1-2 sec. But in our Experiment 9, we gradually increased the target speed from slow to fast. The resource reallocation for change in target speed resembles pouring many times in a given duration (speed change per 0.1 sec), and each time pouring only a little juice from one cup to the other. In this case, there are more opportunities to spill the juice with every extra pour, and the destination cup will end up with less juice than the origin cup had. Similarly, observers are more likely to lose track of the target receiving reallocated resources when the resource reallocation is triggered by changes in speed than by changes in target number. This is because the greater reallocation costs means that the new high resource target does not receive sufficient resources.

Another possible explanation is that humans are very bad at detecting speed change (McBeath et al., 1995; Traszczak, Zinke, & Wegener, 2012) as described in the results section of Experiment 9. During the period of speed changing, observers might be delayed in shifting their attentional resource between targets that switch speeds because they are slow to detect the speed change or even fail to notice it. This means observers have less or no resource to support the increasingly demanding target and then fail in tracking that target. Alternatively they might keep the attentional resource at the original target. To facilitate resource reallocation among targets according to speed change during the trial, a future study might increase the amount of speed change.

The third possible explanation for the failure of resource reallocation in our Experiment 9 is that a cue may be necessary for observers to effectively reallocate resources in response to speed changes. All of the studies that varied the target set provided an

additional cue at the moment of changing the target set to make observers easily direct their attention to the new target set (Wolfe et al., 2007; Ericson & Christensen, 2012). However, in our Experiment 9, participants needed to detect the speed change and reallocate their attentional resource between targets without any help from additional cuing. This might explain why the resource did not reallocate between targets with switching target speeds in Experiment 9. As the previous paragraph described, observers have a poor sensitivity on detecting the speed change. For future investigation, adding an explicit cue to the target of speed change can facilitate detection of the speed change.

#### **4.4.2 Serial Models and Unequal Time-Sharing within a Hemifield**

Unequal allocation of the tracking resource is compatible with both parallel and serial models. According to the parallel account, all the targets' positions are updated simultaneously, but with more resource devoted to a target the positions are updated more accurately.

According to the serial account, target positions are updated one by one. The more targets there are, the less frequently their positions are updated (Howe et al., 2010; Oksama & Hyona, 2008; Tripathy & Howard, 2012; Tripathy et al., 2011). At higher speeds, the targets travel farther between position updates, resulting in a speed limit cost for larger tracking loads, as shown in the experiments of Chapter 2 and 3. In Chapter 3, we found a substantial cost in speed limit when two targets were presented in the same hemifield but having little or no cost when the targets were presented in different hemifields. This might suggest observers serially track multiple objects within one single hemifield but track independently (in parallel) in the two hemifields.

Howe et al. (2010) however provided evidence against serial processing resource allocation for tracking multiple objects within one hemifield with a variation of the classical simultaneous-sequential paradigm (Eriksen & Spencer, 1969; Shiffrin & Gardner, 1972). The

observed tracking performance was better when all the objects moved and paused simultaneously (simultaneous condition) than when half of objects moved then paused while the other half moved (sequential condition). If observers track targets in serial, the performance of sequential condition would be greater than that of simultaneous condition. But if two targets were tracked in parallel, tracking performance should be equal in both the simultaneous and sequential condition. Thus, results from Howe et al. (2010) were compatible with the parallel account and against the serial account when tracking objects within a hemifield. This conclusion may however only rule out a certain class of serial models—those in which the serial process can rapidly (more often than every 500 ms) vary which targets it visits without any cost.

Regarding the allocation issue, serial models have assumed that the positions of all targets are registered equally frequently. However, a serial model could allow for one target to receive a greater share of the tracking focus' time. When more resource is devoted to one target over another, the focus of attention visits that target longer or more frequently than the other. This would accommodate our evidence for flexibility of the resource allocation.

#### **4.4.3 Parallel Models and Differential Resource Allocation**

The first theory of MOT proposed (Pylyshyn & Storm, 1988) is a “slots” or discrete model. According to this model, targets are tracked in parallel and independently, each by its own mental index (FINST) or slot. Because observers are assumed to have four to five FINSTs, the Pylyshyn and Storm (1988) slots theory explicitly predicts that tracking performance will not vary as the number of targets is increased, providing the total number of targets does not exceed the number of FINSTs the observer processes. Similar to experiments of previous chapters, Experiment 9 contradicted this prediction with the finding that speed limit for tracking one target was substantially higher than tracking two targets.

Alvarez and Franconeri (2007) and Vul et al. (2009) proposed continuous resource theories to explain tracking limits. The original notion of continuous resource theory is that less resource is allocated to each target when more targets are tracked, resulting in lower tracking speed limits. Our Experiment 8 provides evidence of varying resource allocation between targets with different speeds. More resource is allocated to the fast target than the slow one, which leads to a higher tracking speed limit for the fast one. This finding can explain the equal tracking accuracy between targets moving at 1 deg/s and at 6 deg/s in the experiment 4 of Liu et al. (2005). If the faster targets had not been allocated more resource, the fast targets should have had much worse performance than the slow targets.

As an alternative to continuous resource theory, Kazanovich and Borisjuk (2006) suggested that objects are tracked by an oscillatory, multi-layer neural network. Because each layer is responsible for tracking a single target, the amount of resource devoted to a target is not predicted to increase if a target moves faster than the other targets in the display. As such, this model does not explain our finding that faster targets can consume more resource than slower targets. However, the model could be modified to allow a single target to be tracked by more than one layer and thereby accommodate our results.

Our results of differential resource allocation might be accommodated with a modified slot theory where each target can be allocated more than one slot (Zhang & Luck, 2008). The modified slot theory resembles a limited set of pre-packaged boxed juice of a fixed size. Such a modified theory was first proposed in a study of visual short-term memory (Zhang & Luck, 2008), in which observers were asked to remember three targets. If for example the limited number of slots were four, then one target would be able to receive more than one slot so that an increase in the memory precision of report was found for that target having more than one slot. Indeed, the average of memory precision of observers' report was shown in the study of the Zhang and Luck (2008), which is different than the slots theory that



having no increase in the average of precision. Under such a model, resource might be differentially allocated and faster targets could be allocated more slots.

For object tracking, Horowitz and Cohen (2010) however demonstrated that flexible resource (FLEX) theory fits better than the modified slots theory for reports of the motion direction of tracked targets. They conducted a similar approach as the Zhang and Luck (2008) in an MOT task to measure the precision reporting of direction representation for tracked targets. When the objects stopped moving, observers rotated an arrow on the target to match the last direction of the target's trajectory. Precision (size of the angular error) declined with increase of target load from one to six tracked targets. This finding was incompatible with the prediction from the modified slots theory that after exceeding observers' capacity the precision would remain constant, and also the prediction of FINST theory that a fixed resolution was found regardless of the number of targets. This left open however the issue of whether other information used in MOT besides motion direction is also fit better by FLEX theory.

Our Experiment 9 also attempts to distinguish the modified slots theory and FLEX theory by the differential resource allocation. According to the modified slots theory (presuming the maximum number of slots is four), it is predicted that in the same-speed condition, each target received two slots (50%) of resource. In the different-speed (other-slow) condition, the slow target received one slot (25%) and the fast target received three slots (75%). The flexible resource theory proposed instead that each target could be allocated any percentage of resource depending on the demands of targets.

Assuming the target in the one-target tracking condition (2.14 rps) consumes 100% of the hemisphere-specific tracking resource and each target in the same-speed condition (1.63 rps) consumes 50% of the resource, based on the speed limit of the faster target in the other-slow condition (1.84 rps), we can calculate how much of the resource was allocated to that

target, if we make an additional assumption. That assumption is that the relationship between target speed limit and proportion of resource allocated to it is linear. Interpolating based on those empirical speed limits, the estimated percentage of resource consumed for the faster target is around 69 % (if 100% = 2.14 rps and 50% = 1.63 rps, 1.84 rps = 69%). While the assumption of a linear resource-versus-speed limit function may not necessarily be true, the percentage that results provides a convenient measure of the improvement in speed limit. However, the 95% confidence interval of this prediction for the faster target (CI: 51.38%~86.71%) in the different-speed unchanged condition covers the expected value for the modified slots theory. Thus, it cannot exclude the possibility of resource allocation predicted by the modified slots theory.

In short, either this continuous resource theory (Alvarez & Franconeri, 2007) or the modified slots theory (Zhang & Luck, 2008), could explain our results of differential resource allocation because the number of tracked targets are not more than four. Future studies might ask observers to track more than four targets to distinguish which theory is correct.

#### **4.4.4 Attention and the Tracking Resource**

Which of the processes involved in tracking are also required for other tasks? Possibly the hemifield-specific resource documented here is used solely for visual tracking and selection, and thus cannot be shared with other tasks. Alternatively, the resource that was differentially allocated in the experiments here may be a general (albeit hemisphere-specific) attentional resource required for many other tasks. Performing visual search simultaneously with having a telephone conversation or discriminating auditory tones can reduce one's tracking ability (Alvarez et al., 2005; Kunar, Carter, Cohen, & Horowitz, 2008; Tombu & Seiffert, 2008). However, whether or not the resource shared with other tasks is hemifield-specific does not appear to have yet been tested. Here we found that the resources that could be differentially allocated among targets were largely hemifield-specific. More work must be

done, especially testing of hemifield specificity of non-tracking tasks, if the present findings are to be connected with other tasks.

This study provides the first evidence for differential allocation of the hemisphere-specific tracking resource between targets. Further work is needed to determine whether differential allocation is under strategic control, and whether other tasks share this hemisphere-specific resource.

#### **4.5 Conclusion of Chapter 4**

In summary, both experiments showed that the speed limit was better for a given target if the second target was slow than if the second target was fast, implying that more resource was allocated to the faster of the two targets. This was significant only for targets presented in the same hemifield, consistent with the theory of independent resources in the two hemifields. Although this differential resource allocation occurred during the target-cuing period, observers might be unable to reallocate the resource according to speed change during the trial at the rate of 1 revolution/sec<sup>2</sup> acceleration/deceleration rate.

## Chapter 5 :Tracking Performance is Constrained by Temporal Resolution

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### 5.1 Introduction of Chapter 5

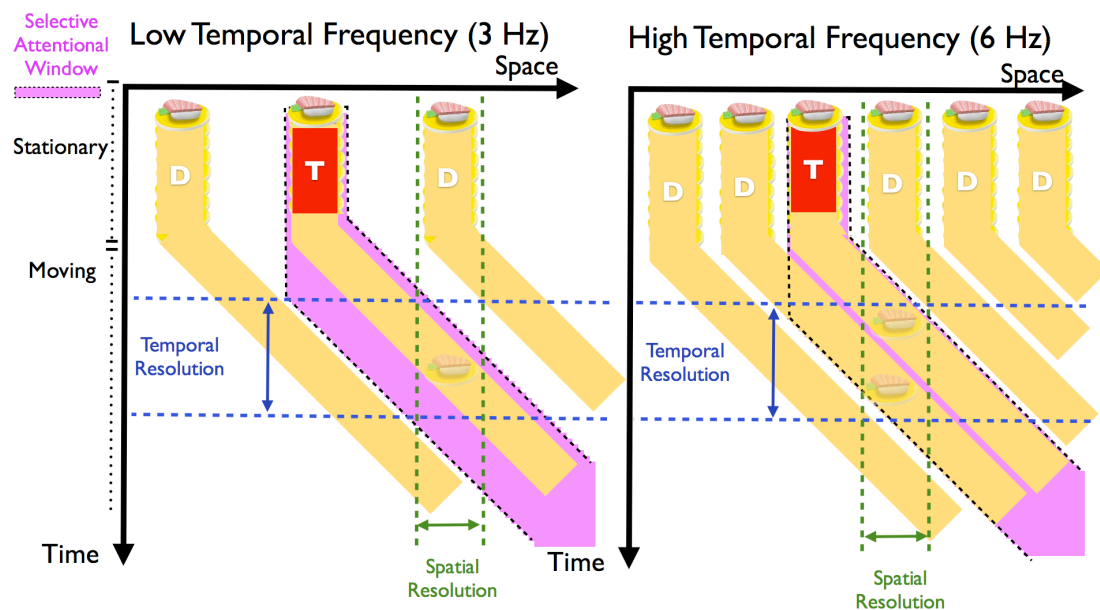
The existence of a limited mental resource mediating the attentional processing of tracking multiple objects was supported by evidence in our previous chapters. Firstly, Chapter 2 reported that splitting the tracking resource among targets reduced the tracking speed limits. The concern of spatial interference was excluded by using widely-spaced targets or equating the travel distance of objects. Then in Chapter 3 we demonstrated this tracking resource is largely hemisphere-specific. The speed limit for tracking two targets presented in bilateral visual hemifields was substantially higher than for two targets presented within one unilateral visual hemifield. Our evidence for differential resource allocation to targets with different speeds further supported the claim of resource theory in Chapter 4. These findings make us confident that the processing of tracking multiple objects is mediated by resources that are at least partially hemisphere-specific.

Does availability of attentional resource affect only the speed limit? When having a dinner at a sushi train restaurant, we need to pay attention to track the tray containing our favourite kind of sushi, as it goes around the train trajectory. If the sushi tray moves faster, more resource is apparently required for tracking it (Chapter 2). As we know, speed is the derivative of space with respect to time.

However, there is another kind of potential temporal limit besides the speed limit. In our experiments within previous chapters, stimulus blobs moved in a circular trajectory, resembling a sushi train. If the tracking speed limit is, say, 1 rps, then at the speed limit in one second it travels one full circuit of the trajectory. If there is only one distracter sharing the trajectory with the target, then during that second, the distracter also passes by each location one time. In our arrangement, the distracter was located opposite the target in the trajectory, so that at 1 rps, after the target passes a location, the distracter passes by it 0.5 s

later. If more distracters are added, evenly spaced about the trajectory, then after the target passes a location, a distracter will pass sooner than 0.5 s. If that interval is too short, observers may be unable to distinguish the target tray from the distractor tray. Researchers usually term the minimum time needed between target and distractor trays as temporal resolution. With display of the circular moving stimuli, to represent the temporal resolution of tracking ability, researchers measure the temporal frequency limit (Verstraten et al., 2000), which is the reciprocal of the temporal resolution. In the current experiments, we also measure the temporal frequency limit.

The space-time diagram illustrates the temporal resolution factor in tracking the sushi tray in conditions of low versus high temporal frequency (Figure 5.1). Verstraten et al. (2000) found evidence that the temporal resolution for tracking one target was 125~250 ms. Although such a temporal resolution is sufficient to individually track one sushi tray in the low temporal frequency condition pictured in Figure 5.1, participants would be unable to indicate which tray was the target sushi in the high temporal frequency condition. As Figure 5.1 shows, in the high temporal frequency condition, more than one sushi tray was within the selective attentional window (purple area) and participants cannot distinguish one from the others. A previous study suggested that spatial resolution reduced when attention is split into multiple foci at disparate locations (Franconeri et al., 2007). However, it is unknown whether temporal resolution reduces as attention is split to track multiple targets. The current experiments in this chapter focus on applying attentional resource theory to the factor of temporal resolution, investigating whether the temporal frequency limit decreases with increasing the number of tracked targets.



**Figure 5.1. The space-time diagram of sushi trays**

At a particular location, a sushi tray appears every 0.33 sec for the 3 Hz condition (Left Panel) whereas a sushi tray appears every 0.16 sec for the 6 Hz condition (Right Panel). If the tracking temporal resolution for an observer is around 0.32 sec (as shown by the purple rectangle; specific selection window of attention), the observer will successfully track a sushi tray over space and time in the 3Hz condition (assuming that any separate speed limit is not exceeded). In the 6 Hz condition, both the target sushi tray and a distracter are included in the selection window of attention (0.32 sec) and therefore the observer cannot individually track the target, owing to their temporal resolution being exceeded.

### 5.1.1 Temporal Limits on Tracking

Human visual processing is constrained by multiple temporal frequency limits (Holcombe, 2009). Most scientists are familiar with the flicker fusion limit- above that temporal frequency, nothing is perceived but the sum of the images being presented. But even at temporal frequencies below the flicker fusion limit, certain visual judgments cannot be made because their temporal frequency limits are much lower than the fusion limit. In the temporal domain, viewing a light alternating between on and off can illuminate the temporal resolution of attention (He et al., 1997). When the temporal frequency of this flicker is over 7-10 Hz, observers are unable to individuate successive states of light and the light is experienced as a constant flicker without discrete appearances and disappearances. This phenomenon is termed *Gestalt* flicker fusion (Van de Grind et al., 1973). The temporal limitation of Gestalt flicker fusion rate was also found in later studies with a number of different tasks. In Battelli et al. (2001)'s study, participants had to discriminate apparent

motion from unmoving flicker and the maximum rate of perceived motion was 8-10 Hz.

Aghdaee and Cavanagh (2007) reported temporal threshold levels of 9-11 Hz when subjects had to distinguish the relative phase of flickering stimuli. Observers had to judge whether two dots flickered either in- or out-of-phase. When two out-of-phase flicker dots were closely spaced in time, subjects saw these dots as undifferentiated flicker.

Rather than testing temporal limits, the majority of experiments studying attentional capacity limits during attentive tracking have focused on the maximum number of targets that can be tracked and on *spatial* properties of moving attention (Intriligator & Cavanagh, 2001). Only Verstraten et al. (2000) tested its temporal limits, and did so only for tracking a single target. They found evidence for two temporal limits, both of which constrain attentive tracking of a moving object- a speed limit and a temporal frequency limit. In one display, several discs were arrayed in a circular trajectory about fixation. All the discs stepped (apparent motion) about fixation, and one of them was designated for tracking. In another display, a continuous radial circular sine wave grating was presented, centred on fixation. Participants were told to track an individual bar of the rotating grating. Verstraten et al. (2000) found that performance declined to 75% by about 1.3 revolutions per second (rps) for the three participants tested. A similar speed limit (1.63 rps, based on a more lenient 57% performance criterion) was found in our Experiment 3 of Chapter 2 with 6 participants, using a similar technique but with moving blobs (one target and two distractors).

Temporal frequency of an individual disc at a fixed location may also be an important limiting factor on performance of attentive tracking. Such a limit may reflect the minimum temporal window tracking can access or the frequency at which each target is sampled by tracking processes. Verstraten et al. (2000) manipulated temporal frequency via variation of object speed and the number of distractors within a circular trajectory. The tracking speed limit decreased with increasing number of displayed discs or bars of the gratings, and the

authors argued that maximum tracking speed might be limited by the variable of temporal frequency (flicker rate) of the discs. For both displays, the maximum temporal frequency rate at which the target could be tracked was 4-8 Hz. In contrast, the direction that the display was rotating could be perceived at much higher rates—up to 25 Hz for the sine wave grating. Although their evidence was not entirely airtight (e.g., they did not correct for change in guessing rates for different number of objects in a ring), the results of our experiments in this chapter support their claims.

Verstraten et al. (2000) tested the limits on tracking only a single target. Extending the flexible resource theory (Alvarez & Franconeri, 2007), it is possible that at higher temporal frequencies of flicker at a location, more attention is needed to create or maintain the motion percept. In other words, more attention is needed to individuate the flicker states when temporal frequency of the target light is higher. According to this theory, increasing the number of tracked targets would split attentional resource among them, yielding less resource per target (Alvarez & Franconeri, 2007). More targets may thus yield lower temporal frequency limits. In the experiments presented here, observers track more than one target at the same time in order to investigate whether attentive tracking will fail at less than the limiting value of temporal frequency in the one-target condition or not. Based on the flexible resource theory and the theory of Gestalt flicker fusion, it is hypothesized that the temporal frequency limit might be lower when tracking more targets.

Two experiments were performed in this chapter to investigate the effect of additional targets on the temporal frequency limit as well as the speed limit. In Experiment 10, we investigated the speed limits and temporal frequency limits for tracking one and for tracking two targets. In Experiment 11, we increased the tracking load, comparing the speed limits and temporal frequency limits for tracking two with tracking three targets. Varying the number of objects in the moving array and the speed of the array revealed both speed limits and



temporal frequency limits. The temporal frequency limit fell from 6.9 Hz with one target to 4 Hz with two targets and 2.6 Hz with three targets. This could be explained by time-sharing among targets of a process that can only operate on one target at a time, or parallel processing that becomes less temporally precise when less resource is available per target. This appears to be the first evidence that temporal frequency limits on high-level processing are set by the availability of a limited resource.

## **5.2 Experiment 10: Two-Ring Experiment**

The purpose of this experiment was to investigate whether the temporal frequency limit declined as the number of tracked targets was increased from one to two. Modifying the stimulus display of the study of the Verstraten et al. (2000), we used two concentric circular trajectories. Varying the number of objects arrayed within a circular trajectory from 3 to 12 and a range of rotation speeds (0.05-2.1 rps) of each trajectory manipulated the temporal frequency. For instance, with 6 objects in the array, a speed of 1.1 rps would be 6.6 Hz.

If the temporal frequency constrains tracking performance and if more attentional resource is needed to track as temporal frequency increases, it is predicted that the temporal frequency limit for tracking one target should be strikingly higher than that for tracking two targets.

### **5.2.1 Method**

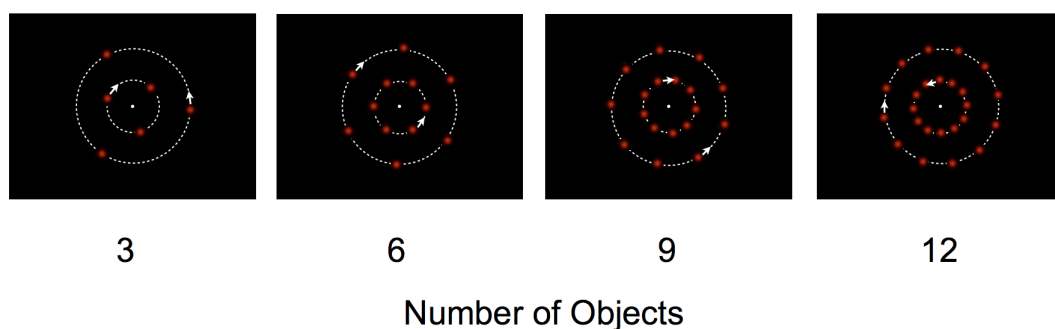
#### **5.2.1.1 Participants**

Six participants (five male, one female, 29-37 years of age) who reported normal or corrected-to-normal vision agreed to participate, following approval of the protocol by the University of Sydney's ethics committee in accordance with the Declaration of Helsinki.

### 5.2.1.2 Stimuli

Stimuli were presented on a 22-inch Mitsubishi Diamond Pro 2070SB CRT monitor (1,024 x 768 resolution) with a refresh rate of 160 Hz controlled by a Mac running a Python program that used PsychoPy software (Peirce, 2007). Viewing distance was 57cm in a dimly lit room, with a chin rest and forehead support to avoid head movements.

The stimulus of this experiment comprised two concentric rings of objects. For each ring, three, six, nine, or twelve objects were evenly spaced about a circular trajectory (Figure 5.2). A white fixation dot (luminance:  $167 \text{ cd/m}^2$ ) with a radius of 0.1 deg was presented at the centre of the display. The background was black ( $< 1 \text{ cd/m}^2$ , screen size 41 deg x 31 deg). In this experiment, the objects were blobs with a Gaussian luminance profile (visible diameter 0.8 deg, luminance:  $12 \text{ cd/m}^2$ ). In order to keep the two rings well outside each other's crowding zone (Intriligator & Cavanagh, 2001; Pelli & Tillman, 2008), the inner ring had radius of 2.5 deg and the outer ring was 5.5 deg. The crowding zone is typically half of the target's eccentricity (Bouma, 1970; Pelli & Tillman, 2008). The separation between inner and outer rings (3 deg) is greater than the crowding zone (2.75 deg). Thus, it is expected that crowding between targets should not occur in this stimulus display.



**Figure 5.2. Schematic of the displays in Experiment 10**

All objects in a ring always moved at the same speed and began in the same direction but the rings occasionally reversed direction independently of the other rings. On different trials, each ring contained 3, 6, 9, or 12 objects, which together with speed determined the temporal frequency. One or two objects in separate rings were designated as targets by appearing in white at the beginning of the trial before becoming red.

### 5.2.1.3 Procedure

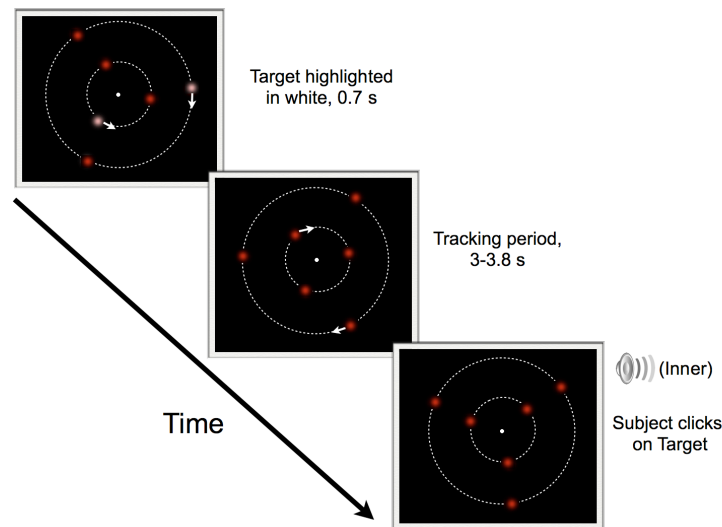
Participants were told to maintain fixation on the white dot at the display centre. For every trial, the initial locations of the blobs were random in each circular trajectory. The blobs in the outer circular trajectory revolved about fixation in the opposite direction from those in the inner circular trajectory. The trial started with the target objects presented in white ( $167 \text{ cd/m}^2$ ) while the remainders (the distracter objects) were red (Figure 5.3). The targets gradually became red (identical to the distracters) over the initial 0.7s, via a linear ramp through RGB space. The subsequent tracking interval was assigned a random duration between 3 and 3.8 s. During the tracking period, the blobs occasionally reversed direction to prevent participants from predicting the final target positions from their initial positions and speeds. Each ring of blobs was independently assigned a series of reversal times, which succeeded each other at random intervals between 1.2 and 2 s. For this experiment's 3 to 3.8s tracking interval, this resulted in 2 or 3 reversals.

In one condition, participants tracked two blobs and in the other, they tracked only one. In the one-target condition, only one blob was designated as a target: For half of trials, the target was in the outer ring and in the other half it was in the inner ring. In the two-target condition, two targets were designated, one in each ring.

At the end of the trial, one ring was indicated with a recording of a person saying “inner” or “outer”. The participants used the mouse to indicate which blob was the target in the corresponding ring. In the two-target condition, in half of trials participants were asked to indicate the target in the inner ring and other half of trials that in the outer ring.

All objects revolved about fixation at the same rate throughout each trial. Speeds from 0.05 to 2.1 rps were used on different trials. They were presented in pseudorandom order and fully crossed with the number of target manipulation: one-target vs. two-target. The speeds for each condition and person were chosen on the basis of piloting. Each person participated

in at least 480 trials of an experiment, which usually involved two sessions, each shorter than fifty minutes.



**Figure 5.3. The trial procedure for all experiments in Chapter 5**

After the targets are highlighted in white, all blobs become red and revolve about the fixation point. During the tracking interval, the blobs on each trajectory occasionally reverse movement direction, at random times independent of the other trajectory. After 3 to 3.8s the blobs stop and one ring is indicated by a recorded voice. Participants clicked on one blob of that ring.

#### 5.2.1.4 Data Analysis

To estimate the “speed limit”, plots of speed versus proportion correct were fit by a logistic regression that spanned from a chance rate to a ceiling level of performance. The chance rate varied with the number of objects in a ring, so a particular performance level such as 75% has a different meaning for distinct object-number conditions. For instance, the chance level was 33% correct with three objects in a ring (two distractors and one target). The chance rate was 17% correct for the six objects, 11% for the nine objects, and 8% for the 12 objects in a ring. Despite guessing rates being unequal, Verstraten et al. (2000) only reported the 75% threshold for all object-number conditions, so their results were difficult to interpret. A level more likely to be comparable across conditions is that halfway between the chance level and the ceiling imposed by the lapse rate, which allowed varying from 0 % to 10% to get the best estimate for each condition and each participant. This threshold adjusted for chance rate is named as “midpoint threshold”.

We examined both the midpoint threshold and the 75% threshold, as Verstraten et al. (2000) did. Because the pattern of results was very similar or identical for both thresholds, we reported the “speed limit” in this experiment according to the midpoint threshold at which performance fell to the value midway between ceiling and chance. This speed limit was estimated separately for each participant and condition.

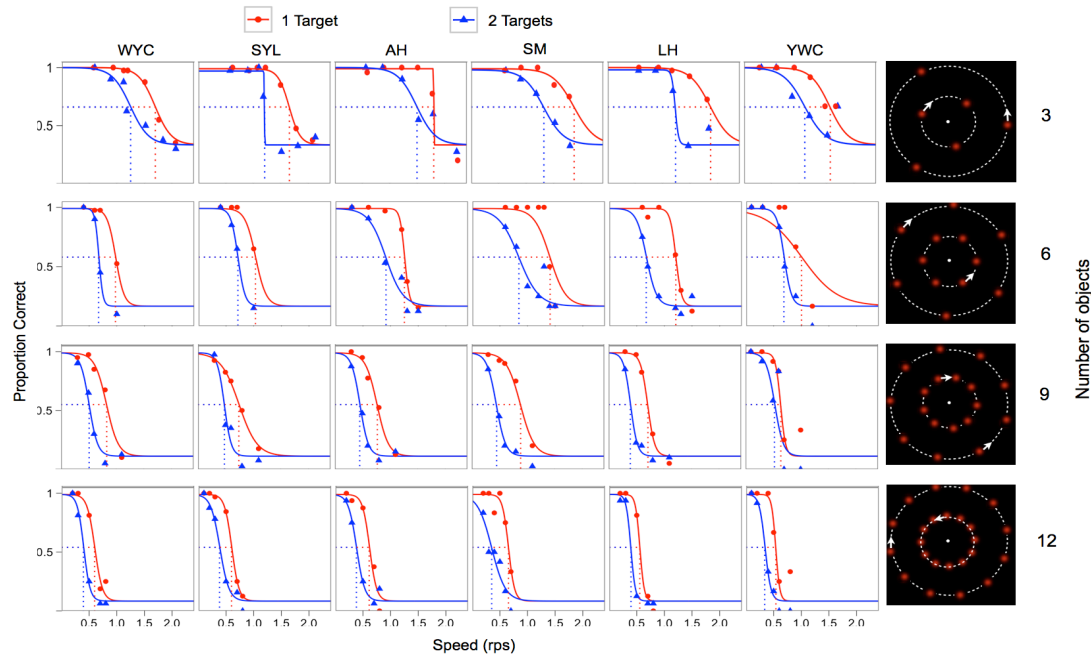
The temporal frequency limit was measured by using different numbers of objects along one circular trajectory and object rotation rates. For instance, with 6 objects in the array, a speed of 1.1 rps would be 6.6 Hz. In this experiment, two approaches were used to estimate the “temporal frequency limit”. Firstly, the temporal frequency limit was directly converted from the speed limit in all number-object conditions. For example, the speed limit 1.7 rps was converted to the temporal frequency limit 5.1 Hz for three objects in a ring. An alternative approach was to fit psychometric functions to temporal frequencies rather than speeds. The temporal frequency limit was also calculated with the midpoint threshold estimation.

Because the similar or same pattern of results resulted from both approaches for all conditions, in the following results and discussion part, we only reported the second approach.

### **5.2.2 Results and discussion**

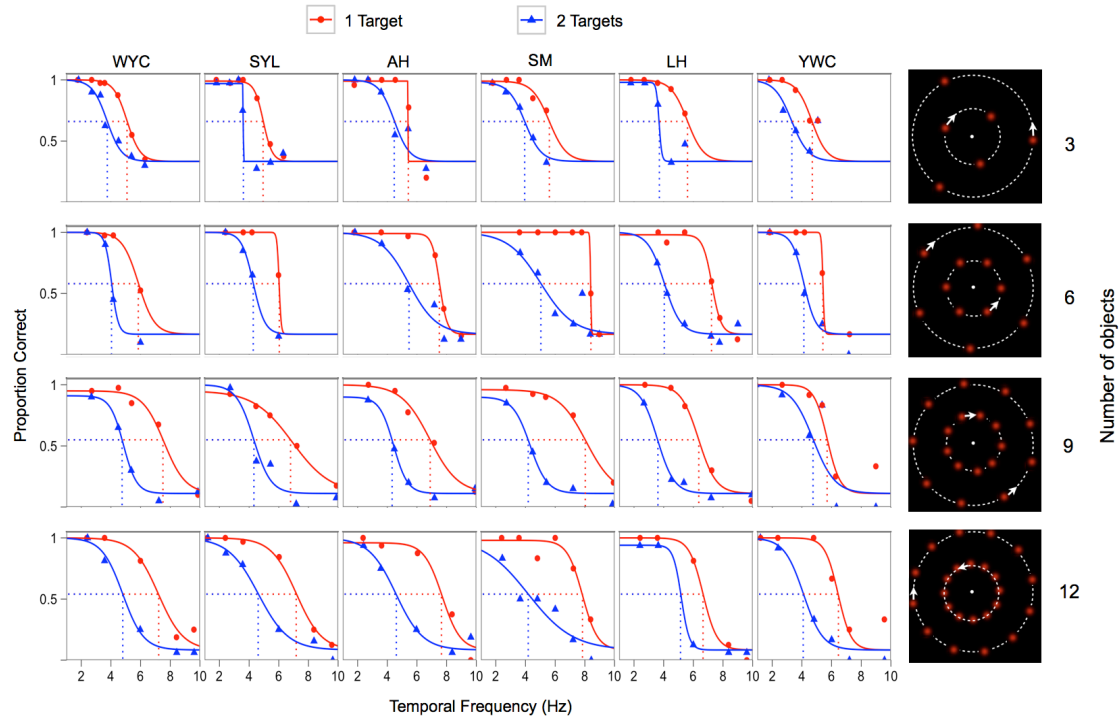
The data and associated psychometric plots for each of the six participants in four object-number conditions (3, 6, 9 and 12 objects) of Experiment 10 are shown in Figure 5.4 and 5.5. Performance declines as speed or temporal frequency increases. The speed limit and temporal frequency limit was reported according to the midpoint threshold at which performance falls to the value midway between ceiling and chance (66% for 3 objects, 58% for 6 objects, 55% for 9 objects, and 54% for 12 objects). For every participant, the speed

limit and temporal frequency limit for tracking one target was substantially higher than for tracking two targets no matter how many number of objects in a ring.



**Figure 5.4. Data and psychometric fits with Speed in Experiment 10**

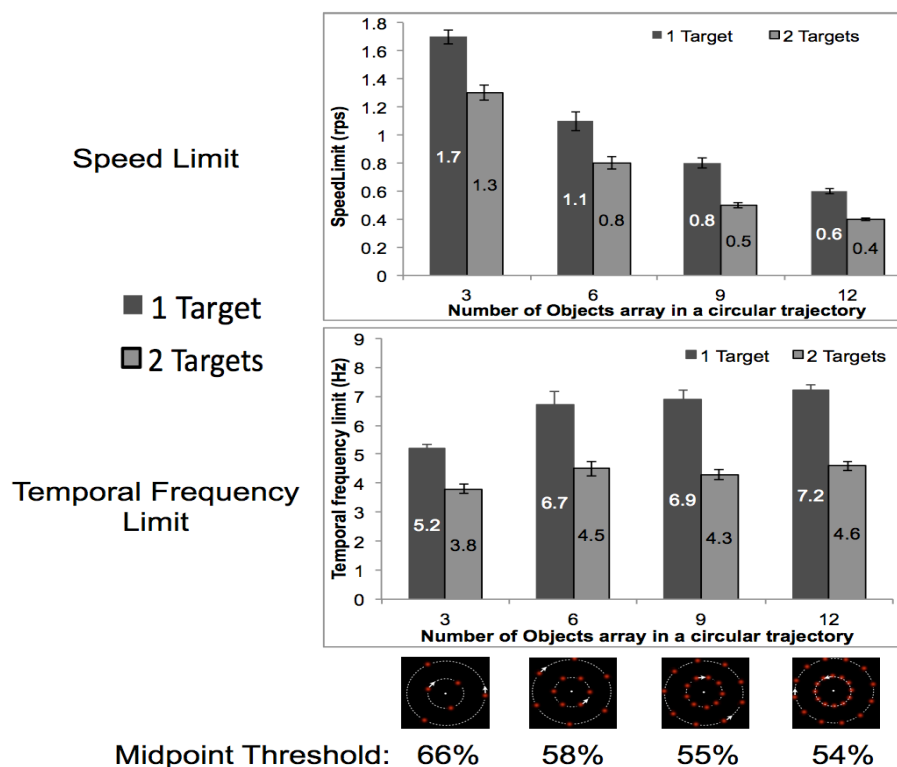
Proportion correct is shown for each speed, in the one-target (red curve) and two-target (blue curve) conditions. Dotted lines show the midpoint thresholds.



**Figure 5.5. Data and psychometric fits with Temporal Frequency in Experiment 10**

Proportion correct is shown for each temporal frequency, in the one-target (red curve) and two-target (blue curve) conditions. Dotted lines show the midpoint thresholds.

The mean speed limits and temporal frequency limits across 6 participants for each condition are shown in Figure 5.6. For tracking one target, with only three objects in a ring (leftmost column of the graph), the average speed limit across participants was 1.7 rps (similar to the 1.63 rps in Experiment 3 of Chapter 2 which used similar stimuli but with equal travel distance across speeds). As the number of objects in the rings increased from 3 to 12, the speed limit substantially declined to 0.6 rps (simple linear regression for 3 to 12:  $b=-0.126$ ,  $r^2=0.875$ ,  $t(23)=-12.407$ ,  $p<0.001$ ; for 6 to 12:  $b=-0.087$ ,  $r^2=0.757$ ,  $t(17)=-7.062$ ,  $p<0.001$ ). As we explain below, there is reason to believe the 3-object condition may reflect a speed limit while 6 to 12 objects reflects a temporal frequency limit, so we sometimes analysed these conditions separately.



**Figure 5.6. Results of Experiment 10 for Averaged Performance**

The mean speed limits (top panel) and temporal frequency limits (bottom panel) across participants in Experiment 10, for tracking one target (dark grey bar) and two targets (light grey bar) within four different number of object conditions. Error bars are one standard error across participants.

A temporal frequency limit on attentive tracking can explain why the speed limits decline with increasing numbers of objects in the circular trajectory. Apparently, the speed

limit on tracking objects is not the sole limiting factor on tracking performance. If object tracking is only constrained by the maximum speed for targets that we can track, as the number of objects in a ring increases, the speed limit should not decline. However, a temporal frequency limit predicts the present pattern of a decline in speed limits with number of objects. Temporal frequency is the product of speed and number of objects in a circular trajectory. If temporal frequency constrained attentive tracking, the corresponding speed limit is lower for larger number of objects in a ring.

Evidence that a temporal frequency limit indeed constrained tracking performance is that the temporal frequency limits were constant across different number of object conditions. For the 6, 9, and 12 object conditions of one-target condition in Figure 5.6, the average temporal frequency limit was fairly constant at 6.7 to 7.2 Hz (simple linear regression indicates a nearly flat line:  $b=0.071$ ,  $r^2=0.046$ ,  $t(17)=0.873$ ,  $p=0.395$ ).

The three-object condition may have instead been constrained by speed limit rather than temporal frequency limit. This explains the corresponding temporal frequency limit (5.2 Hz) was lower - a repeated-measures ANOVA with number of objects and number of targets as factors revealed a number of objects effect,  $F(3, 15)=14.141$ ,  $p<0.001$ , partial  $\eta^2=0.739$ , and a post-hoc test indicated the temporal frequency limit for the 3 object condition was significantly lower than that for the 6 ( $p=0.004$ ), 9 ( $p=0.003$ ), and 12 ( $p<0.001$ ) object condition. This finding is comparable to that of Verstraten et al. (2000) that tracking performance was constrained by a speed limit of under 2.0 rps when only a few objects were in the ring. In other words, with only three objects in a ring, the speed limit was hit before the temporal frequency limit was exceeded. To clarify this, for the 6 to 12 object conditions, participants were unable to track a target over the temporal frequency limit of 6.9 Hz although the speeds were below 1.7 rps, meaning that 6.9 Hz is the constraint on performance. But for the 3-object condition, the maximum target speed that observers could



track was 1.7 rps, which corresponds to 5.1 Hz, below the putative temporal frequency limit of 6.9 Hz. Therefore, it appears that the constraints on performance are a 1.7 rps speed limit and 6.9 Hz temporal frequency limit. The failure of tracking occurred when either of these limits was exceeded.

### 5.2.2.1 Effect of Target Number on Tracking Limits

Consistent with the experiments in Chapters 2 and 3, the target number effect on tracking speed limits was observed in all conditions of this experiment. The speed limit was lower for tracking two targets than for tracking one target for every number-of-objects condition, paired t-tests applied to each condition yielded a  $p$ -value of 0.001 or less (3 objects:  $t(5) = 10.404$ , Cohen's  $d = 4.254$ ; 6 objects:  $t(5) = 6.588$ , Cohen's  $d = 3.287$ ; 9 objects:  $t(5) = 7.15$ , Cohen's  $d = 3.038$ ; 12 objects:  $t(5) = 9.127$ , Cohen's  $d = 3.779$ ).

A critical finding was that the temporal frequency limit declined with increasing target loads. For the 6 to 12 object conditions, the temporal frequency limit was lower for tracking two targets (~4.5 Hz) than for tracking one target (~6.9 Hz). A repeated-measures ANOVA with number of object and number of targets as factors showed a significant target number effect  $F(1, 5) = 80.015$ ,  $p < 0.001$ , partial  $\eta^2 = 0.941$ . In addition, a striking target number effect was also found according to the ANOVA after the 3-object condition (where performance might be limited by speed not temporal frequency) was included,  $F(1, 5) = 101.634$ ,  $p < 0.001$ , partial  $\eta^2 = 0.953$ .

Unlike other number-of-object conditions, with three objects in a ring the decrease in tracking performance with increasing target loads might result from the constraint on speed rather than temporal frequency. For the two-target condition, the 3.8 Hz of the 3-object condition was significantly worse than the mean 4.5 Hz of other number-of-object conditions,  $t(20) = -3.062$ ,  $p = 0.006$  according to a contrast analysis, manifesting a lower temporal frequency limit for 3 objects than for more objects. This suggested that the speed limit

decreased to 1.3 rps as increasing target loads caused by the constraint on speed rather than temporal frequency. If the temporal frequency limit was hit first, the speed limit for tracking two targets could reach to 1.5 rps that corresponded to 4.5 Hz. A speed limit was visible because the constraint on speed (1.3 rps) was hit first.

### **5.2.2.2 Concern of Spatial Interference**

Spatial interference might be the main concern that could threaten the theory that tracking performance was constrained by temporal frequency limits. As the number of objects in a ring was increased, the temporal frequency increased but also the spacing between objects decreased.

The spatial characteristics of crowding with a single target have been studied extensively (Pelli & Tillman, 2008; Toet & Levi, 1992). “Bouma’s Law” (Bouma, 1970) was validated by Pelli and Tillman (2008) - that for objects arrayed in the radial direction from the fixation outside fovea, perception of many aspects of each object is impaired when they are closer than half their eccentricity. For objects arrayed at a common eccentricity (isoeccentrically), as are the objects within each of our rings, the zone of spatial interference is substantially smaller than the Bouma’s law figure of half the eccentricity (Toet & Levi, 1992). But to be conservative, we will consider the implications of the half-the-eccentricity figure. It implies that crowding should not occur as long as the number of objects ( $n$ ) is fewer than 13. The reason is that when  $n$  objects are equally spaced about a circle centred on fixation, they will be separated by greater than half their eccentricity ( $e$ ) as long as  $n$  is fewer than 13. This follows because the separation between the objects is  $2\pi e/n$ , which is less than  $0.5e$  as long as  $n$  is fewer than 13. As crowding within our isoeccentric rings should not occur until the separation is smaller than this, we reasoned that no crowding should occur when  $n=12$  or below, and did not use conditions with greater than 12 objects.

In this experiment, the crowding was avoided by using large distances between one ring and another, and the distances were chosen to be large enough to be substantially greater than half each ring's eccentricity.

In the context of tracking multiple objects, Franconeri and colleagues have proposed that limitations on tracking are entirely owing to spatial interference rather than attentional resource allocation (Franconeri, 2013; Franconeri et al., 2010; Franconeri et al., 2008). Their conclusions were based on displays in which collisions were allowed between objects and therefore minimum separations were much smaller than allowed in our displays. Thus, spatial interference might explain a lowering of the maximum performance for larger numbers of objects in a ring. However, spatial interference should reduce the performance at all speeds, which corresponds to lowering the ceiling on proportion correct or increasing the lapse rate term in the psychometric fit. Franconeri and colleagues have emphasized that spatial interference may become greater with speed because in a typical MOT display with random trajectories, at higher speeds targets will travel farther and be involved in more close passes. But separation was controlled here and in any case spatial interference should occur at all speeds, including slow ones. If it did not, it would not be truly spatial interference. The spatial interference account therefore predicts that performance should be worse for more targets and/or more distracters, even at very slow speeds.

To investigate whether spatial interference occurred at very slow speeds, the “lapse rate” parameter was used to compare the performances for tracking one and two targets across four different number-of-object conditions. If spatial interference were impairing tracking, it should occur more for conditions with higher target numbers and inflate the lapse rate. Conversely, little to no change in lapse rate was presented as the number of objects and targets increased. The target number effect ( $F(1, 5) = 3.596, p = 0.116$ , partial  $\eta^2 = 0.418$ ) and its interaction ( $F(3, 15) = 0.809, p = 0.508$ , partial  $\eta^2 = 0.139$ ) were non-significant but a

significant object number effect ( $F(3, 15) = 3.906, p = 0.03$ , partial  $\eta^2 = 0.439$ ) was found according to a repeated-measures ANOVA with number of objects and target numbers as factors. In fact, the significant object number effect resulted from the highest lapse rate (0.05) for 9 objects in the two-target condition (see Table 5.1). This special highest lapse rate did not extend to the 12-object condition, so we suggested it is not owing to spatial interference and may be owing to random variation. In addition, as shown from Table 5.1, the lapse rate of the 12-object condition was similar to the others. Therefore, there is no evidence of crowding or spatial interference from the analysis of lapse rate.

In addition to analyses of lapse rate, we also examine the effect of number of targets and objects on performance at only the slowest speed. According to the spatial interference theory, larger number of objects or targets will yield worse performance even at slowest speed. However, no significant effects of target number ( $F(1, 5) = 4.16, p = 0.097$ , partial  $\eta^2 = 0.454$ ) and object number ( $F(3, 15) = 2.88, p = 0.071$ , partial  $\eta^2 = 0.366$ ) were found, and their interaction ( $F(3, 15) = 3.048, p = 0.061$ , partial  $\eta^2 = 0.379$ ) also was non-significant according to a repeated-measures ANOVA that included the factors of number of targets and number of objects. So, this comparison on performance as tracking targets at the slowest speed also contradicts the theory of spatial interference.

**Table 5.1. Estimated lapse rates for different number of objects and targets in Experiment 10**

| Objects | 1 Target | 2 Targets |
|---------|----------|-----------|
| 3       | .01± .01 | .01± .01  |
| 6       | .01± .01 | .0± .0    |
| 9       | .02± .03 | .05± .05  |
| 12      | .01± .02 | .01± .02  |

*Note.* Lapse rates ± Standard error across participants

### 5.2.2.3 Effect of Eccentricity

Aghdaee and Cavanagh (2007) found the temporal resolution of attention was independent of visual field location by investigating the limits relative phase judgments of two flickering lights. Their findings showed that the temporal frequency limit has a little

decrease with eccentricity, which is substantially smaller than the eccentricity effect of spatial resolution of attention (Intriligator & Cavanagh, 2001). If the tracking performance limited by the temporal resolution reflects the same processing as the experiments of the Aghdaee and Cavanagh (2007), the constraints on tracking performance should have little or no change with eccentricity.

To examine the effect of eccentricity on temporal limits, we report statistics separately between the 3-object condition that is likely to be limited by speed and the rest conditions that appear to be limited by temporal frequency. For the 3-object condition, a repeated-measures ANOVA with eccentricity (2.5 or 5.5 deg) and target number (tracking 1 or tracking 2 targets) as factors showed the eccentricity effect ( $F(1, 5) = 2.093, p = 0.208$ , partial  $\eta^2 = 0.295$ ) was not significant and no interaction ( $F(1, 5) = 2.691, p = 0.162$ , partial  $\eta^2 = 0.35$ ) was found on speed limits. For the remaining conditions (6 to 12 objects), the eccentricity effect ( $F(1, 5) = 0.081, p = 0.788$ , partial  $\eta^2 = 0.016$ ) and its interactions (target\*eccentricity:  $F(1, 5) = 0.065, p = 0.809$ , partial  $\eta^2 = 0.013$ ; object\*eccentricity:  $F(2, 10) = 1.319, p = 0.31$ , partial  $\eta^2 = 0.209$ ; target\*object\*eccentricity:  $F(2, 10) = 7.934, p = 0.009$ , partial  $\eta^2 = 0.613$ ) were also non-significant on temporal frequency limits according to a repeated-measures ANOVA that included number of objects as well as eccentricity and target number.

The average speed limit (temporal frequency limit) across all conditions for a single target was 1.1 rps (6.7Hz) at 2.5 deg and 1.0 rps (6.5Hz) at 5.5 deg and for two targets 0.7 rps (4.3 Hz) at 2.5 deg and 5.5 deg. This result also suggested the speed limit is imposed not by linear speed, which was much greater for larger eccentricity, but rather by rotation speed (revolutions per second). It might be explained by a limit on tracking object per unit area of retinotopic cortex, as that scales linearly with eccentricity.

#### 5.2.2.4 Capacity-one benchmark

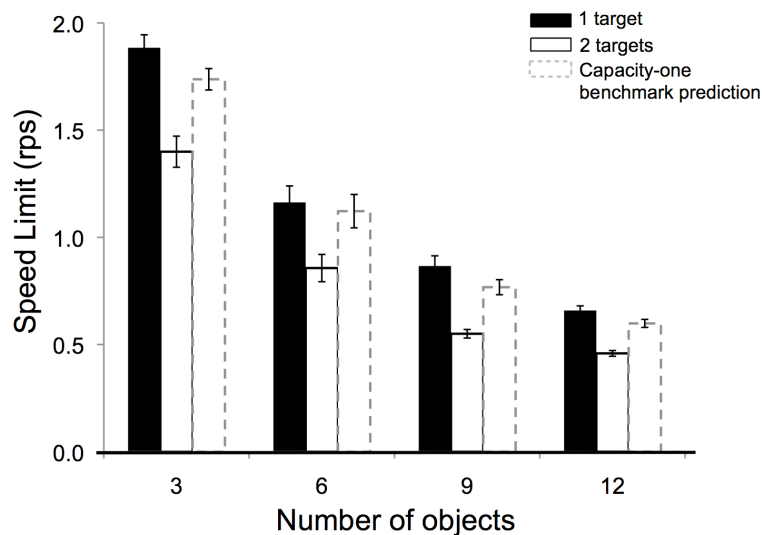
As with all the experiments in Chapters 2 and 3, here we also calculated the predictions of the two-target speed limit using the capacity-one benchmark. On this benchmark, for the half of trials where participants track the target that will be asked in the end of trial, the predicted performance is similar to the performance of tracking one target. On the other half of trials where asked for the untracked target at the end, participants need to guess and therefore perform at chance. Taking the 3-object condition as an example, the two-target predicted performance logistic curve fit spanned from 66% (99.33% for the half trials and 33% for the other half of trials) to 33% (chance rate).

Because the maximum proportion correct for the predicted logistic curve and the chance rate varied with the number of objects in a ring, we determined the speed limit with the midpoint thresholds across four different number-of-object conditions (50% for 3 objects, 38% for 6 objects, 33% for 9 objects, and 31% for 12 objects).

Figure 5.7 illustrates the empirical speed limit for tracking one and two targets as well as the speed limit predicted by the capacity-one benchmark across four number-of-object conditions. For all conditions, the empirical speed limits were even slower than the benchmark speed limits. Statistically, a repeated-measures ANOVA shows a significant difference between the empirical and benchmark speed limits for tracking two targets,  $F(1, 5) = 58.22, p = 0.001$ , partial  $\eta^2 = 0.921$ . The reason that participants did more poorly than if they had tracked just one is likely that they attempted to track both targets but did not have sufficient tracking resources to track two targets, so they got both wrong.

We suggest that when the speed is so high that participants can only track one object, they nonetheless persist in attempting to track two or three, and by continuing to split their resources in this way they end up unable to track any, not even one. This implies that the resource-versus-performance function (Norman & Bobrow, 1975) is sufficiently steep that at

high speeds, dividing resource in two causes performance to fall farther than halfway towards chance. The implication is that the two targets do not trade off linearly (the performance operating characteristic, Norman & Bobrow, 1975) but rather taking half the resource from one decreases performance by more than the corresponding factor of two.



**Figure 5.7. The capacity-one benchmark prediction**

The speed limit for tracking two targets is significantly worse than the speed limit for tracking one, and is also substantially lower than that predicted by the capacity-one benchmark (dashed bars). Error bars show one standard error across 6 participants.

### 5.3 Experiment 11: Three-Ring Experiment

The result of Experiment 10 that the temporal frequency limits declined as the target number increased can be explained by the resource theory. More attentional resource was allocated to the target when there was only one enhanced the temporal resolution of tracking it and therefore improved the temporal frequency limits.

However, an alternative explanation for this finding is that tracking one target might be special. For some cognitive functions, it seems that humans can conduct only one at a time (Allen & Madden, 1990). In the two-target condition, only one of the targets would benefit from this cognitive processing to improve the tracking performance. We therefore went on to examine the effect of load with more targets, so that any benefit of cognition for a single target would be more similar for the various target loads. Because we also intended to keep

the targets very widely separated, we could not increase using many targets- we compared two to three.

Experiment 11 was similar to Experiment 10, but compared two targets to three rather than two to one. The number of objects in the circular trajectories and the rotational speeds were varied to investigate the temporal limits. According to resource theory, the temporal frequency limit should be lower for tracking three targets than that for the two-target condition.

### **5.3.1 Method**

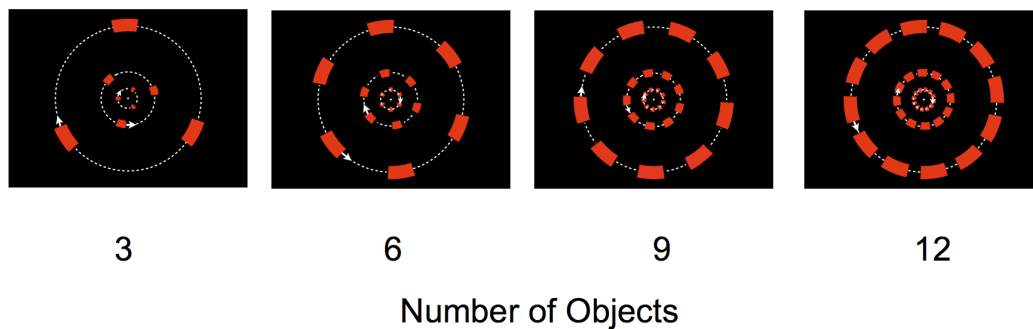
#### **5.3.1.1 Participants**

Seven participants (6 male, one female, 29-37 years of age) were recruited in Experiment 11, and six of them had also previously participated in Experiment 10.

#### **5.3.1.2 Stimuli**

With the following exceptions, the apparatus and stimuli employed in this experiment were identical to those in Experiment 10. In Experiment 10, the stimuli comprised of two concentric rings of objects whereas three concentric rings of objects were used in this experiment (Figure 5.8). Instead of the Gaussian blobs, the objects were arc segments with thickness and length scaled by eccentricity of the three rings (for inner: 0.6 deg x 0.9 deg; middle: 1.6 x 1.4 deg; outer: 4.3 x 2.4 deg). To keep the rings well outside each other's crowding zones (Intriligator & Cavanagh, 2001; Pelli & Tillman, 2008), the three rings had radii 1.5, 4.5, and 12 deg. Similar to Experiment 10, all separations among three rings were greater than the crowding zone. For example, the separation between outer and middle rings (7.5 deg) was larger than the 6 deg of the crowding zone of the outer ring. The separation between inner and middle rings (3 deg) was also larger than the 2.25 deg of the crowding zone of the middle ring.





**Figure 5.8. Schematic of the displays in Experiment 11**

All objects in a ring always moved at the same speed and the same direction but occasionally reversed direction, independently of the other rings. On different trials, each ring contained 3, 6, 9, or 12 objects, which together with speed determined the temporal frequency. Two or three objects in separate rings were designated as targets by appearing in white at the beginning of the trial before becoming red.

### 5.3.1.3 Procedure

The sequence of events on a given trial was identical to that of Experiment 10. All objects began at random points in their trajectories (although all were equally spaced about the trajectory), with the inner and outer objects revolving about fixation initially in the opposite direction from those in the middle trajectory. Targets were indicated by showing the objects as white as the motion began. They gradually became the same colour as the distracters (red) over the next 0.7s, via a linear ramp through RGB space. The objects in each trajectory occasionally reversed direction—each trajectory was independently assigned reversal times that succeeded each other at random intervals between 1.2 and 2 s. The total tracking interval varied randomly between 3.0 and 3.8 s.

In one condition, participants tracked two targets (chosen randomly from three trajectories on each trial) and in the other, they tracked three targets, one in each trajectory. At the end of the trial, a sound recording indicated in which ring the participants should use the mouse to indicate which blob was a target. In one-third of trials participants were prompted to indicate the target in the inner trajectory, in 1/3 of trials in the middle trajectory and other 1/3 of trials in the outer trajectory.

All objects revolved about fixation at the same rate throughout each trial. A range of speeds from 0.05 to 1.6 rps was used on different trials. Those were presented in

pseudorandom order and fully crossed with the two-target versus three-target conditions. The speeds for each condition and person were chosen on the basis of piloting. Each person participated in at least 480 trials of an experiment, which usually involved two sessions, each shorter than fifty minutes.

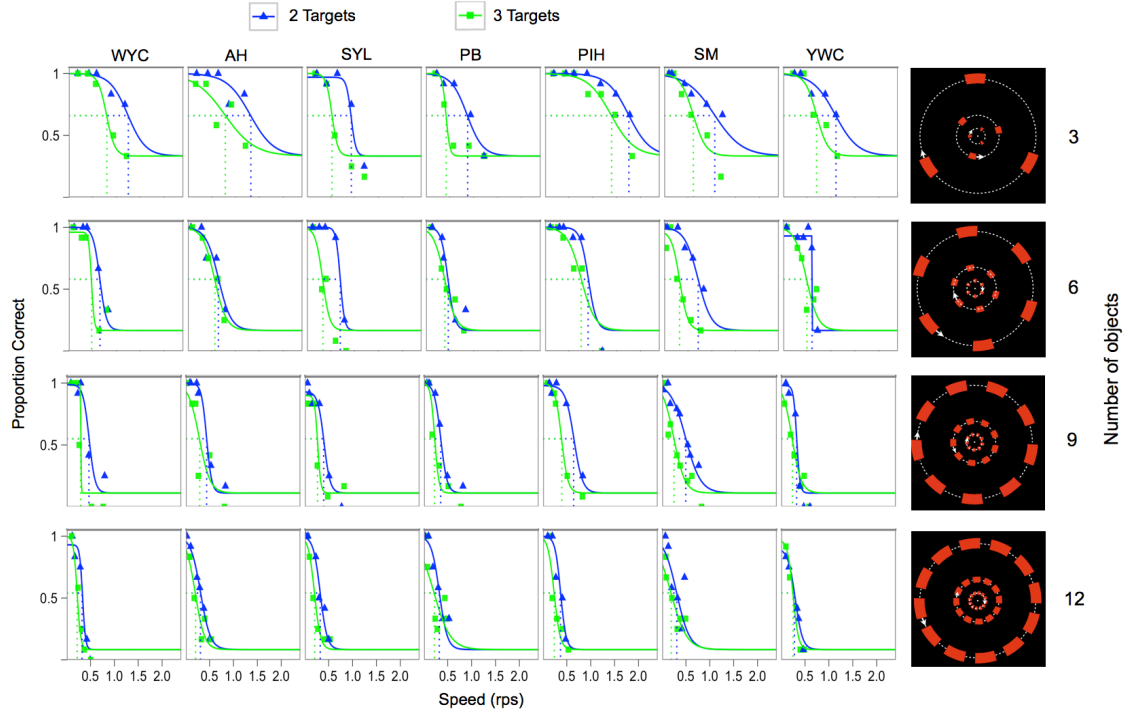
### 5.3.2 Results and discussion

The effects of speed and temporal frequency on proportion correct are plotted in Figure 5.9 and 5.10, for tracking two and tracking three targets within the four different number-of-object conditions (3, 6, 9 and 12 objects) of Experiment 11. For every participant, the speed limit and temporal frequency limit (midpoint threshold) for tracking two targets are higher than for tracking three targets across four conditions.

The mean speed limits and temporal frequency limits across 7 participants for each condition are plotted in Figure 5.11. Consistent with Experiment 10, for tracking two targets, a 0.9 rps decrement in speed limit was found as number of objects in a ring increased from 3 to 12 (simple linear regression for 3 to 12 objects:  $b=-0.094$ ,  $r^2=0.739$ ,  $t(27)=-8.576$ ,  $p<0.001$ ; for 6 to 12 objects:  $b=-0.058$ ,  $r^2=0.698$ ,  $t(17)=-6.627$ ,  $p<0.001$ ). For tracking three targets, there was also a decrease of speed limits as the number of objects in a ring increased from 3 to 12 (simple linear regression for 3 to 12 objects:  $b=-0.06$ ,  $r^2=0.573$ ,  $t(27)=-5.907$ ,  $p<0.001$ ; for 6 to 12 objects:  $b=-0.043$ ,  $r^2=0.565$ ,  $t(17)=-4.971$ ,  $p<0.001$ ).

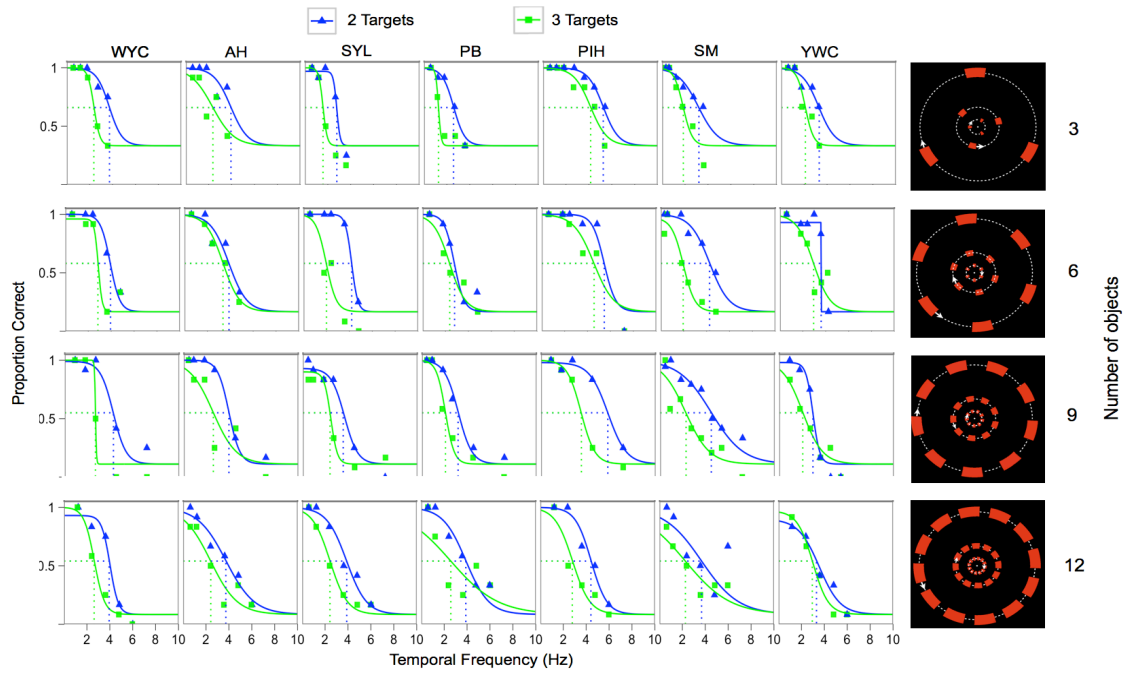
Extending Experiment 10 to higher target loads, speed limits were much slower for three targets than for two targets in each number of objects condition (from 3 to 12, paired  $t(6)=21.206$ ,  $t(6)=3.754$ ,  $t(6)=7.204$ ,  $t(6)=8$ , all  $p$ -values were less than 0.01).

The hypothesis that a ~4Hz limit for two targets constrained tracking performance was corroborated by the similar results in Experiments 10 and 11. The two experiments had a similar temporal frequency limit despite the use of different stimuli (mean 4.5 Hz in Experiment 10 and mean 3.9 Hz in Experiment 11).



**Figure 5.9. Data and Psychometric fits in Experiment 11**

Proportion correct is shown for each speed, in the two-target (blue curve) and three-target (green curve) conditions. Dotted lines show the midpoint thresholds.

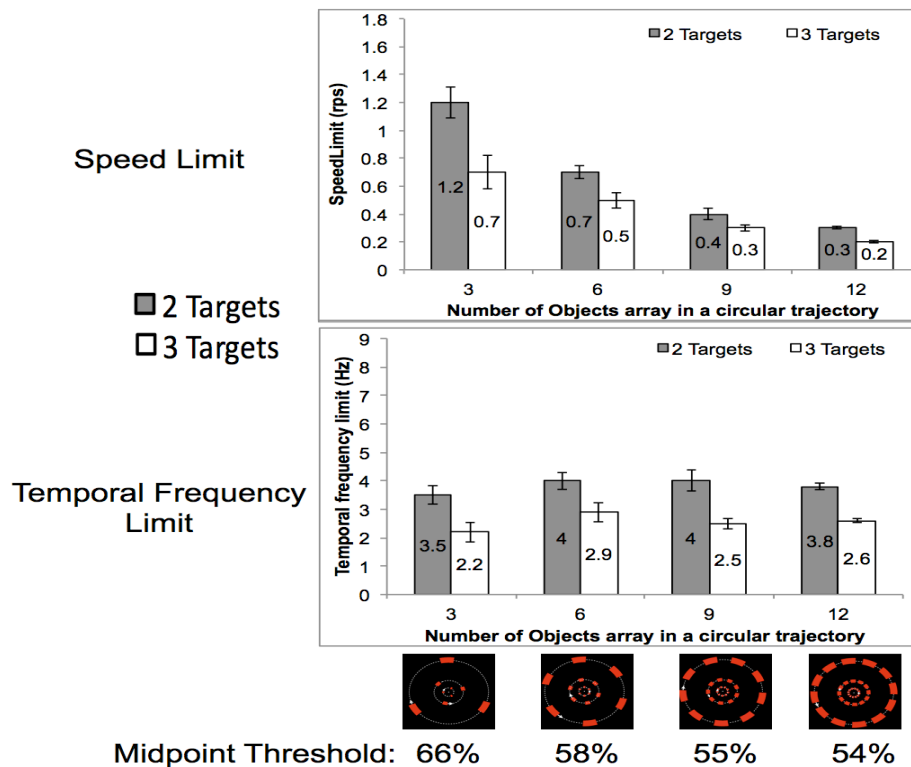


**Figure 5.10. Data and Psychometric fits in Experiment 11**

Proportion correct is shown for each speed, in the two-target (blue curve) and three-target (green curve) conditions. Dotted lines show the midpoint thresholds.

In this experiment, the temporal frequency limits were also substantially poorer for the larger load of three targets. A repeated-measures ANOVA with number of objects (3, 6, 9

and 12) and number of targets (two vs. three) as factors indicated that the 2.5 Hz limit for three targets was significantly lower than the 3.9 Hz limit for two targets,  $F(1, 6) = 102.381$ ,  $p < 0.001$ . A significant target number effect was also found according to the ANOVA after the 3-object condition (where performance might be limited by speed rather than temporal frequency) was excluded,  $F(1, 6) = 56.873$ ,  $p < 0.001$ .



**Figure 5.11. Results of Experiment 11 for Averaged Performance**

The mean speed limits (top panel) and temporal frequency limits (bottom panel) across participants in Experiment 11, for tracking two targets (light grey bar) and three targets (white bar) for the different number of object conditions. Error bars are one standard error across participants.

For tracking three targets, it is no longer possible to see whether a speed constraint limits performance in the 3-object condition. For the 3-object condition, the empirical speed limit (0.8 rps) is similar to the corresponding speed limit (0.87 rps) converted from the temporal frequency limit (2.6 Hz), making it unclear whether it is speed or temporal frequency that constrains tracking performance. The temporal frequency limit for the 3-object condition (2.2 Hz) was not significantly different from the mean of other number-of-object conditions (2.7 Hz), according to a contrast analysis,  $t(24) = -1.312$ ,  $p = 0.202$ .

### 5.3.2.1 Concern of Spatial Interference

To address the possibility of spatial interference, lapse rate and tracking performances at the slowest speed were analysed, just as in the previous experiment. According to the spatial interference hypothesis, the lapse rate should be inflated and tracking accuracy at the slowest speed should reduce with more targets or larger numbers of objects in a ring. For analysis of the lapse rate, a repeated-measures ANOVA with target number and number of objects as factors indicated that the effects of number of targets ( $F(1, 6) = 1.326, p = 0.293$ , partial  $\eta^2 = 0.181$ ) and number of objects ( $F(3, 18) = 0.61, p = 0.617$ , partial  $\eta^2 = 0.092$ ) were non-significant, and neither was the interaction ( $F(3, 18) = 0.919, p = 0.452$ , partial  $\eta^2 = 0.133$ ). The fitted lapse rates are shown in Table 5.2. The lapse rates for the conditions with different target number or different numbers of objects in a ring were similar to each other, around 0 to 0.2.

**Table 5.2. Estimated lapse rates for different number of objects and targets in Experiment 11**

| Objects | 2 Target  | 3 Targets |
|---------|-----------|-----------|
| 3       | 0 ± .01   | 0 ± 0     |
| 6       | .01 ± .03 | .01 ± .02 |
| 9       | .02 ± .02 | .01 ± .04 |
| 12      | .02 ± .04 | 0 ± .01   |

*Note.* Lapse rates ± Standard error across participants

With regard to performance at the slowest speed, it provides little or no evidence of spatial interference. A repeated-measures ANOVA with number of objects and number of targets as factors yielded no significant effect of target number ( $F(1, 6) = 5.76, p = 0.053$ , partial  $\eta^2 = 0.49$ ), a non-significant object number effect ( $F(3, 18) = 0.972, p = 0.428$ , partial  $\eta^2 = 0.139$ ), and no interaction between target and object number ( $F(3, 18) = 0.385, p = 0.765$ , partial  $\eta^2 = 0.06$ ). A post-hoc test revealed that the near-significant effect of the additional target was caused by a deficit for the 6-object condition. For example, the accuracy for the slowest speed for 6 objects (91%) is significantly worse than for the 9 object condition (100%

correct),  $p=0.018$ . It certainly does not fit with the spatial interference prediction of worst performance for the 12-objects condition.

Examining the effect of the separation of the targets on performance also did not yield evidence consistent with the spatial interference theory. The three rings had radii 1.5, 4.5, and 12 degrees, and when observers were asked to track two targets, the two rings with the targets were either inner/middle, middle/outer, or inner/outer. In the inner/outer condition, the separation between the two targets was much greater than in the other conditions. The spatial interference hypothesis was examined by testing the effect of condition on the speed limit. A repeated-measures ANOVA found no significant effect,  $F(2, 12)=0.048$ ,  $p=0.953$ , partial  $\eta^2=0.008$ . Examining the conditions more specifically, paired t-test also showed no significant difference on speed limits between inner/outer vs. inner/middle (from 3 to 12 objects condition,  $t(6)=0.113$ ,  $t(6)=0.649$ ,  $t(6)=-0.441$ ,  $t(6)=-0.629$ , all  $p$ -values are higher than .05) and inner/outer vs. middle/outer (from 3 to 12 objects condition,  $t(6)=0.594$ ,  $t(6)=-0.959$ ,  $t(6)=0.111$ ,  $t(6)=0.468$ , all  $p$ -values are higher than .05).

### **5.3.2.2 Effect of eccentricity**

Consistent with Experiment 10, no effect of eccentricity on tracking performance was found in this experiment. The statistics below are also reported separately for the 3-object condition and others because the 3-object condition may be limited by a separate, speed-limited mechanism whereas the others appear to be limited by temporal frequency. For the 3-object condition, a repeated-measures ANOVA with eccentricity and target number as factors indicated eccentricity is not significant ( $F(2, 12)=0.409$ ,  $p=0.673$ , partial  $\eta^2=0.064$ ) and neither is the interaction ( $F(2, 12)=0.927$ ,  $p=0.422$ , partial  $\eta^2=0.134$ ). For the remaining conditions (6 to 12 objects), neither the eccentricity effect ( $F(2, 12)=3.503$ ,  $p=0.063$ , partial  $\eta^2=0.369$ ) nor its interactions (target\*eccentricity:  $F(2, 12)=0.221$ ,  $p=0.805$ , partial  $\eta^2=0.036$ ; object\*eccentricity:  $F(4, 24)=1.138$ ,  $p=0.362$ , partial  $\eta^2=0.159$ ; target\*object\*

eccentricity:  $F(4, 24) = 0.692$ ,  $p = 0.605$ , partial  $\eta^2 = 0.103$ ) were significant according to a repeated-measures ANOVA that included number of objects as well as eccentricity and target number.

The mean speed limit across four object conditions for two targets was 0.7 rps at 1.5 deg and 4.5 deg, and 0.6 rps at 12 deg. For tracking three targets, the mean speed limit was 0.4 rps at 1.5 deg, 0.5 rps at 4.5 deg and 0.6 rps at 12 deg.

#### **5.4 Discussion of Experiments 10-11.**

Both speed limits and temporal frequency limits were evident when participants tracked a single target. The speed at which one could no longer track was determined by which constraint on performance was exceeded first: the speed limit at 1.7 rps or the temporal frequency limit at 6.9 Hz. Tracking additional targets lowered both speed limits and temporal frequency limits. Temporal frequency limits decreased from 6.9 Hz for one target to about 4 Hz for two targets and 2.6 Hz for three targets. Additionally, the speed limit declined from 1.7 rps to 1.3 rps when the number of tracked targets increased from one to two.

Published theories of tracking have focused on explaining the effects of speed, spacing, and number of targets. Our study is the first evidence to investigate the effect of number of targets on temporal frequency limits of tracking. In these experiments, speed and object spacing were varied and temporal frequency was found to be the primary constraint on tracking performance.

Theories positing that spatial interference is the primary constraint on tracking performance cannot explain our results (Franconeri et al., 2010; Franconeri et al., 2008). In both experiments in this chapter, crowding was avoided by using wide spacing between objects and the separations were chosen to be large enough to be outside the crowding zone of Bouma's law (Bouma, 1970; Pelli & Tillman, 2008). Testing for spatial interference by

examining the effect of target number or object number at very slow speeds yielded no evidence.

#### **5.4.1 Parallel Theories of Tracking- Flexible Resource Theory**

The load-dependence of temporal frequency limits may be explained by both parallel and serial processing theories. The flexible resource theory (Alvarez & Franconeri, 2007) is a parallel processing theory that proposes tracking is mediated by a finite attentional resource that is distributed among the targets. Targets are processed in parallel and independently, and allocating more resource to a target benefits performance. The generic theory does not specify however in what way more resource is beneficial. It might reduce spatial interference by narrowing the tracking foci (Shim et al., 2008), but this would not explain the present results. It might alternatively improve temporal resolution by reducing the temporal selection window, which could explain the present results.

Temporal frequency likely constrained performance because the temporal selection window of tracking was so large that participants were unable to temporally isolate the target from the distractors. Taking the sushi train example described in the beginning of this chapter, participants cannot distinguish which tray is the target sushi when the one after the target arrives too quickly. Thus, the duration of the temporal selection window is a determining factor for tracking. Here, we measured the temporal frequency limit to quantify the duration of the selection window. For instance, a 2.5 Hz limit indicates that performance will be negatively affected when a distractor occupies a temporal selection window within 400 ms of a target. To explain the present data with flexible resource theory, less resource allocated to each target lengthens the temporal selection window and therefore lowers temporal frequency limits.

In addition to explaining the change in temporal frequency limits, more resource might also somehow increase the speed at which the tracking foci can move, which can



accommodate our speed limit finding. To explain the present data, all resource allocated to one target can make its tracking foci move as fast as 1.7 rps. But when tracking two targets, only half of resource is allocated to each target and 1.3 rps is the speed limit.

#### **5.4.2 Serial Switching Theories of Tracking**

In a serial switching theory of tracking (Oksama & Hyona, 2008; Tripathy et al., 2011), only one target can be tracked at a given time. This theory assumes a single focus of tracking rapidly switches among targets to update their location information one at a time. Every time a target is attended by the tracking focus, the current location of the target is recorded and stored. When returning attention to a target, observers recognize the target by judging which object is the closest one to the target's last-sampled location. The critical determining variable of successful tracking should then be half of the inter-sampling interval, which is the duration between two subsequent samplings. When a distractor arrives at a former target location within half of the inter-sampling interval after previous location sampling, tracking will fail by misrecognizing the distractor as a target. The particular interval between location updates therefore naturally predicts a corresponding temporal frequency limit. For example, a 6.9 Hz temporal frequency limit (corresponding to 145 ms) on tracking resulted from that a distractor is closer to the target's sampled location after exactly half of the cycle duration (72.5 ms).

The serial switching theory predicts that temporal frequency limits should decline dramatically with increasing number of tracked targets. For tracking two targets, each target will be visited only half as often, and therefore the critical cycle duration should be double. Our results are not far from this prediction. In Experiment 11, the 4 Hz limit (250 ms) observed here for tracking two targets indicates that 62.5 ms are required to sample one target location and switch to the other. The predicted results for 3 targets are then 2.67 Hz (375 ms), similar to the mean 2.6 Hz observed in Experiment 11. The empirical temporal frequency

limit (4.4 Hz) for two targets is also not far from the predicted result (3.5 Hz) with one-target limit of tracking in Experiment 10.

These temporal frequency limits can also explain some aspects of performance in typical MOT experiments although the displays are different. The objects moved in a circular trajectory that frequently passed the same locations for Experiment 10 and 11 whereas objects move in a random trajectory in typical MOT conditions. Most previous researchers of MOT rarely use speeds that were higher than the speed limit documented here, but the targets in their displays likely do run afoul of the temporal frequency limits. For instance, a 2.6 Hz temporal frequency limits for tracking three targets in Experiment 11 suggested that tracking performance will be poor in the typical MOT experiments when a distractor occupies a region within 385ms of a target occupying it. When tracking more than three targets, tracking may be impossible when the interval between a target and a distractor successively occupying the same region is even larger than 385 ms. Corresponding patterns of movement should frequently occur in the random trajectories used in typical MOT experiments.

The serial switching explanation does not account for the speed limit constraint on performance that occurs with 3 objects in a circular trajectory before the temporal frequency limit is reached. To explain the speed limit cost with the serial switching sampling theory, one could assume that if the target moves far enough from its last-sampled location then the spotlight does not re-acquire the target, even without any distractor nearby. With a higher number of tracked targets, the target will have travelled further since the last location update, reducing the speed limit.

Pylyshyn and Storm (1988) refuted the serial switching theory by that attention spotlight was unable to sufficiently fast switch among locations that are further apart. However, results since then have provided evidence that attention does not take longer to shift between larger distances (Kwak et al., 1991; Shih & Sperling, 2002). S. P. Tripathy et

al. (2011) further pointed out that the traces of the moving objects are likely transiently recorded in the iconic memory buffer, facilitating target recovery in the traditional MOT task. Participants can successfully track multiple objects in serial processing by matching the trace information in the iconic memory buffer and the current locations.

Broadly speaking, tracking multiple objects in a serial approach also involves the flexible allocation of tracking resource. Observers successively switch all tracking resource among targets during the tracking period. Across time (time-sharing), the tracking resource is flexibly shared among tracked targets. For example, if observers were asked to track three targets, each target received all resource in one-third of the tracking period. To explain our finding that temporal frequency limits decreased when more targets were tracked, it can be accommodated by assuming that when observers track fewer targets, each target is allocated more amount of total tracking resource, which is the product of resource and tracking duration.

#### **5.4.3 Difference between Temporal and Spatial Limits on Tracking**

Numerous studies have suggested that spatial and temporal properties of visual attention are mediated by different cortical networks (Aghdaee & Cavanagh, 2007; Battelli et al., 2001; Battelli, Pascual-Leone, & Cavanagh, 2007; Battelli, Walsh, Pascual-Leone, & Cavanagh, 2008). The contralateral parietal cortex mediates the visual spatial attention in one hemifield (Battelli et al., 2001; Culham et al., 1998). For instance, the parietal network in the right hemisphere mediates spatial attention in the left visual hemifield. In contrast, only the right inferior parietal lobe underlies temporal attention in both left and right visual hemifields (Battelli et al., 2007; Battelli et al., 2008; VanRullen, Pascual-Leone, & Battelli, 2008).

A series of studies conducted in patients with parietal cortex damage by Battelli and colleagues provide evidence for the difference of cortical networks mediating spatial versus temporal resolution (Battelli et al., 2001; Battelli, Cavanagh, Martini, & Barton, 2003;

Battelli et al., 2007; Battelli et al., 2008). Battelli et al. (2001) demonstrated that a patient with right parietal damage has slow temporal selection rates in both right and left visual hemifields to judge whether the display is a static flickering of four dots or is an apparent motion of two dots. But patients only have worse spatial attention in the contralateral visual hemifield. Battelli et al. (2007) documented that patients with right parietal lesion were severely impaired in both hemifields for a task of temporal processing of detecting whether there is an odd item among six squares that alternated black and white or all squares are identical. However, patients with left parietal lesion did not have lower temporal processing rates.

Another significant difference between spatial and temporal attention is in terms of the attention resolution across the visual field. Firstly, spatial resolution is much finer in the lower visual field than in the upper visual field (Intriligator & Cavanagh, 2001), which supports the finding in the monkey study that more visual inputs were received in the lower part of the parietal cortex than in the upper part (Maunsell & Newsome, 1987). However, there is no difference between lower and upper visual field for temporal resolution (Aghdaee & Cavanagh, 2007), where temporal resolution was measured by asking observers to judge the relative phase of two flicking lights. Secondly, the spatial resolution of attention dramatically declined from near the fovea to the periphery (Intriligator & Cavanagh, 2001), but the temporal resolution of attention only has a small decrease with eccentricity (Aghdaee & Cavanagh, 2007). These findings indicate that the temporal resolution of attention is independent of visual field location, which differs markedly from spatial resolution of attention.

Both experiments in this chapter also investigate the relationship between the tracking performance and eccentricity. We found the absence of an effect of eccentricity on temporal limits in both experiments. This suggests that temporal resolution is one of the constraints on

tracking multiple objects, and the temporal limits on tracking performance might reflect the same processing that limits relative phase judgments of two flickering lights.

### **5.5 Conclusion of Chapter 5**

Attentive tracking of a moving target was constrained by both a speed limit and a temporal frequency limit. The finding was consistent with the study of the Verstraten et al. (2000), and specifically presented that the constraint on temporal frequency involved more than the constraint on speed as increasing the number of objects in a circular trajectory. In the 3-object condition, the tracking performance was impaired by the speed limit whereas the performance was impaired by the temporal frequency limit when number of objects was 6 to 12. Flexible resource theory and serial switching theory both might explain the cost of additional targets on speed limits and temporal frequency limits.

## **Chapter 6 :General Discussion and Conclusion**

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Here, multiple object tracking was used to explore the limitations of attentional selection. Two decades ago, most researchers investigated attentional capacity limitation via dual-task experiments (Pashler, 1994; Pashler & Johnston, 1998). These demonstrated that adding a second different task has a cost for performance of the first task. Unlike dual-task experiments, here we investigated whether capacity limitation also has a cost when observers perform just one task like multiple object tracking (MOT), but additional targets are added. The results demonstrated that the speed limit or temporal frequency limits of each target declined when more targets needed to be tracked. This indicates that the mental processing for tracking multiple moving objects has limited capacity.

### **6.1 Resource Theory Accounts for the Performance of Multiple Object Tracking**

A variety of theoretical models have been proposed to explain the attentional capacity limitation. Pashler (1994) outlined the three most influential models: resource theory (Kahneman, 1973), central bottleneck theory (Broadbent, 1958), and cross-talk theory (Kinsbourne, 1981). Our results are more consistent with the resource theory than others. The following sections will discuss this in detail.

#### **6.1.1 Excluding Cross-Talk Theory**

Cross-talk theory predicts that the interference between two tasks depends on similarity of the mental representations involved in each (Kinsbourne, 1981). Processing each task is mediated by a specific area of cortex. If two tasks are processed by the same neural population, the cross-talk will occur and lead to large interference between these two tasks.

In this thesis, the possibility of cross-talk interference between targets rather than between tasks was explored. Tracking of targets may be performed by neurons in the superior parietal lobule or intraparietal sulcus (Culham et al., 1998; Howe, Horowitz, Morocz, Wolfe, & Livingstone, 2009; Jovicich et al., 2001). When two targets are close to each other, perhaps

they share some neurons of the superior parietal lobule, leading to a large interference between the mental representations of targets. This idea that targets close to each other on the screen are closer in retinotopic cortex and hence interfere with each other amounts to a spatial interference theory of tracking limits (Franconeri, 2013; Franconeri et al., 2010; Franconeri et al., 2008). But the present experiments demonstrate that the attentive tracking of objects is mediated by a finite tracking resource and the effect of speed on tracking performance is independent of spatial interference.

Spatial interference on visual attention includes target-distractor interference and target-target interference. The target-distractor interference has been extensively studied with the spatial resolution of attention in psychophysical studies of crowding (Intriligator & Cavanagh, 2001; Pelli & Tillman, 2008). In these studies, performance declines owing to the poor spatial resolution to distinguish targets from distractors when they are close together (crowding effect). These studies already found the crowding spacing, that is the critical distance between targets and distractors causing the crowding effect, for target identification (Pelli & Tillman, 2008) and for target selection (Intriligator & Cavanagh, 2001). To avoid this possibility of crowding effect, the separation between targets and distractors in all experiments of my thesis is greater than these crowding spacings.

To investigate whether target-target spatial interference influences our results, comparing narrow separation to wide separation between objects, our Experiment 1 demonstrated that both separations had similar speed limits for tracking one and tracking two targets. Moreover, using a very large separation between objects to better guarantee that no spatial interference occurred, our Experiment 1b found a similar result as Experiment 1. Furthermore, manipulating four target-target separations (3, 5, 7, and 9 deg) within one single hemifield in Experiment 7, speed limits showed little to no change across four separations both for tracking one and for tracking two targets.

Our Experiment 11 also provided evidence against the theory of competition for cortical representation. In Experiment 11, the three rings had radii 1.5, 4.5, and 12 degrees. Each target might be cued in two of three rings for the two-target tracking condition. The spatial interference effect on speed limits was measured by comparisons among three conditions: inner/middle, middle/outer, and inner/outer. No significant differences were found among these three conditions, suggesting again that the effect of number of targets was not dependent on spatial separation. These above results speak against the possibility of cross-talk interference between targets.

Spatial interference of attention between targets has been explored in an alternative form of neural network: oscillatory neural networks, which might be more suitable for object-based attention (Kazanovich & Borisyuk, 2002, 2006). The network operates in phase-frequency space, which explains the interference in non-retinotopic brain areas that the attentional focus is not mediated by a specific area of cortex. The oscillatory neural networks include two main components: central oscillators (COs), which are assembly of neurons that represent the central executive of the attentional system, and peripheral oscillators (POs), which are an assembly of cortical neurons in the primary visual cortex. The focus of attention is formed by synchronous oscillations of these COs and POs. For object tracking, Kazanovich and Borisyuk (2006) suggested that the focus of attentional system is divided into several subsystems, and each subsystem is mediated by an oscillatory neural network that is responsible for tracking a single target. When a target is attended, the assembly of cortical neurons that related to the target (PO) works synchronously with the assembly of neurons that represents the central executive (CO) with a particular phase-frequency space. When a target moves, the new population of cortical neurons must join the synchronized assembly (synchrony) and the neurons representing the old location must leave the assembly (desynchrony). The synchrony and desynchrony take time to complete, which imposes a



speed limit with additional targets to be tracked only if they must be done serially. The spatial interference between two targets might be caused by that the two oscillatory neural networks of COs and POs synchronously oscillate with the same phase-frequency space. The network of the phase-frequency space is different from a retinotopic cortex that is relevant to the Franconeri (2008; 2010; 2013). Therefore, this model of oscillatory neural networks might explain the spatial interference (cross-talk) occurs regardless of separations. This accommodates our results that tracking performance is independent of spatial separation between targets.

For the issue of temporal frequency limits, although Kazanovich and Borisjuk (2006) did not consider, their model may also predict the temporal frequency limit decreases with tracking load. Because it takes time to dynamically synchronize and desynchronize the population of cortical neurons when targets move, the failure of tracking occurs if a distractor arrives at the former target location when those neurons are still partially synchronized. However, to reconcile these results in Chapter 4 with this model, it should be modified to allow a single target to be tracked by more than one oscillatory neural network. In this case, one target having more oscillatory neural networks could be tracked much faster than the target having only one oscillatory neural network.

The present thesis does not completely deny the spatial interference effect on tracking performance, but just claims that speed has an effect on attentive tracking independent of the spatial interference. When the number of close encounters is held constant (equal travel distance) and spatial interference is avoided with wide separation, the maximum speed at which observers can successfully track targets nevertheless declines with additional targets that be tracked (Chapters 2 and 3). When two targets are too close to each other, tracking performance might also be impaired by spatial interference between targets. Further investigation might focus on determining for various small separations how much effect there

is of spatial interference or cross-talk interference. The possible approach is to investigate whether the speed limit decreases much when the separation between targets is less than 3 deg, which is the minimal distance used in our Experiment 7.

### **6.1.2 Rejecting the Central Bottleneck Theory**

According to the central bottleneck theory, certain mental operations are carried out one-by-one, in series (Broadbent, 1958). Our attention can only process one task or target at a given time and we must switch attention between tasks or targets. When two tasks require a critical mental operation at the same time, one task will be delayed or not occur at all, even if two tasks are presented in separate hemifields (Pashler et al., 1994; Ptito, Brisson, Dell'Acqua, Lassonde, & Jolicoeur, 2009).

Two prominent experimental paradigms have highlighted the processing limitation of central bottleneck theory: the psychological refractory period (PRP) paradigm and the attentional blink (AB) paradigm. When observers attempt to perform two tasks at the same time, they are severely delayed the second task processing, which are termed the “PRP effect”. When observers attempt to identify two targets in a rapid serial visual presentation (RSVP) of distractors, they impaired at detecting the second of two targets when it is presented within 300-500ms of the first target, which are termed the “AB effect”. Both paradigms have a common phenomenon that observers can only process one target or task at a given time and serially switch processing between targets or between tasks. With the PRP paradigm, Pashler et al. (1994) demonstrated the delayed processing of one stimulus in one visual hemifield (Task 2) is caused by another stimulus requiring processing in the opposite hemifield (Task 1) for split-brain patients as well as neurologically intact participants. With the AB paradigm, Ptito et al. (2009) found, regardless of when two targets were presented sequentially within the same hemifield or across separate hemifields, the AB effect exists for both neurologically intact participants and split-brain patients, and no significant difference

on AB effect was shown within the same hemifield and across separate hemifields. For split-brain patients, the right and left hemispheres are completely independent because of a complete section of the corpus callosum but their subcortical structures are intact. Results of these two studies supported the central bottleneck theory, and suggested that the serial processing of central bottleneck theory might be mediated by the subcortical structures instead of cortices (Pashler et al., 1994; Ptito et al., 2009), which is different from the retinotopic neural networks of cross-talk theory.

Our results are incompatible with the central bottleneck theory because we found that tracking resources are largely hemisphere-specific. If there is only one central bottleneck processing one target at a time, it is hard to explain why performance is better when targets were presented in separate hemifields than in the same hemifield (Chapter 3). It is also difficult to reconcile our results in Experiment 8 with the central bottleneck theory. In Experiment 8, the tracking resource could be differentially allocated between targets of different speeds only in the same hemifield, not across two hemifields (Chapter 4).

However, one could modify the central bottleneck model to propose a separate bottleneck in each hemisphere. According to this dual-bottleneck theory, for multiple targets in a single hemifield, processing must switch between the targets in series, such that only one target can be processed at a given time with that hemisphere-specific bottleneck. In the following paragraphs, the issue of serial or parallel tracking is discussed to consider whether the dual-bottleneck theory is congruent with our results.

The independence of tracking in the two hemifields shows that tracking is parallel inasmuch as there is concurrent independent processing in the two hemispheres, which is inconsistent with the central bottleneck theory. But within a hemifield, the findings of our experiments are compatible with both parallel (flexible resource theory) and serial (serial switching theory) models. In serial accounts, at higher speeds the targets travel farther

between position updates, resulting in a speed limit cost for larger tracking loads. A larger temporal frequency limit cost for adding target numbers results from a longer inter-sampling interval, which is the duration between two subsequent samplings. When a distractor arrives at a former target location within half of the inter-sampling interval after previous location sampling, tracking will fail by misrecognizing the distractor as a target (serial sampling). In a parallel account, the larger speed limit cost and temporal frequency limit cost for additional targets results from less resource is allocated to each target. Less resource received by each target might reduce the speed of the tracking focus or increase the duration of temporal selection window.

Both serial and parallel models can also explain that the reduction of speed limit with adding one target in the same hemifield is similar to that predicted if observers can only track one target and guess the other (capacity-one benchmark) in Chapter 3. At high speeds, successful tracking requires observers to quickly switch this one-capacity resource between two targets within one hemifield (serial tracking). As the capacity-one benchmark and linear resource-versus-performance function accounts both make the same prediction, parallel processing with 50% of the resource per target also fits with our results at high speeds (parallel tracking). At slow speeds, the empirical tracking performance was substantially better than that predicted by capacity-one benchmark, indicating observers can track more than one target at lower tracking load (parallel tracking). In some cases of our experiments, empirical speed limits for tracking two targets are even worse than the capacity-one benchmark. On a serial account, it indicates that splitting the attentional resource between two targets over the timeline of a tracking trial does not yield enough tracking focus' time (resource) on each target so performance is worse than the capacity-one benchmark. On a parallel account, it indicates that splitting the attentional resource between two targets means there is not enough resource to successfully track either.

In Chapter 4, unequal allocation of the tracking resource within one single hemifield is also compatible these two models. On a parallel account, all the targets' positions are updated simultaneously, but with more resource devoted to a target the positions are updated more accurately. On a serial account, more resource is devoted to one target than the other, and the focus of attention visits that target longer or more frequently than the other. A better performance of the target paired with a slow-speed target than paired with a same-speed target might result from more resource is allocated to that target or longer duration the focus of attention visits that target. Therefore, the dual-bottleneck theory is unable to be refuted by our findings because both parallel and serial models are congruent with our results when targets are presented within one hemifield.

Broadly speaking, serial processing can be considered a particular variant of resource theory, where the resource is time-shared among the targets or tasks. All the resource is allocated to one target or task and attention rapidly switches between two targets or tasks in turn. Unlike parallel tracking theories, such as flexible resource theory, the resource is flexibly allocated between targets or tasks in terms of time. For example, 40% of the trial duration attention is allocated to task A and 60% of the trial duration attention is allocated to task B. As the number of targets increases, each is processed proportionally less often by the serial process. This concern might offer insight into why both parallel and serial models are consistent with our results.

To sum up, the central bottleneck theory is disconfirmed by showing that tracking resources are largely hemisphere-specific. The findings that performance is better when targets are presented in separate hemifields than in the same hemifield, indicating two independent tracking resources can process targets in their own hemifields. However, the modified bottleneck theory that each hemifield has its bottleneck could explain our results. Previous literature related to bottleneck theory was primarily focused on dual-task

experiments. The present thesis is the first to our knowledge to discuss the bottleneck theory on tracking multiple targets. Our results do not exclude the theory that each hemisphere has its own bottleneck because serial processing of tracking targets within a hemifield remains viable. To distinguish which theory is better for interpreting multiple object tracking, further investigation must identify an appropriate method by which serial and parallel processing can be distinguished, which has been a long-time concern in psychology.

Contrary to the theory by which the central bottleneck is mediated by a subcortical structure, a series of many functional magnetic resonance imaging (fMRI) studies that have shown the neural mechanisms underlying the capacity limitation of the MOT task are the posterior parietal cortex (Culham et al., 1998; Howe et al., 2009; Jovicich et al., 2001). Thus, this differential mediating networks between the MOT studies and the central bottleneck theory might interpret why our results are inconsistent to the central bottleneck theory. In other words, the dual-bottleneck theory mentioned above that reconciles our results might be mediated by the similar neural networks as these fMRI studies.

### **6.1.3 Supporting Resource Theory**

Excluding both cross-talk theory and central bottleneck theory discussed above, a tracking resource mediating the attentional processing of tracking multiple objects was supported by the evidence in this thesis. Three main aspects of the resource theory were described in Chapter 1. Firstly, resource is allocated in a graded manner, and performance rises with the amount of resource deployed (Kahneman, 1973; Logan, 1997). Secondly, the resource is limited and must be divided among several concurrent attentional processes. Finally, the resource can be flexibly allocated among several processes so that some processes receive more resource than others. Our results support these three aspects.

Pylyshyn and Storm (1988) proposed a slot model theory of the fixed-resource theory of visual capacity limits, known as the FINST model. According to this model, each target is

independently tracked by a mental pointer known as a FINST. Such a slot model is distinct from resource theories that posit graded rather than discrete allocation. Because each observer has only four to five FINSTs, the model explicitly predicts that tracking performance will not vary as the number of targets is increased until the maximum number of mental points is exceeded, whereupon it will decline with additional targets.

All experiments in this thesis contradicted this prediction. The speed limit decreased with increasing the number of tracked targets even below Pylyshyn and Storm (1988)'s limit of four targets. In the two-ring and three-ring experiments (Experiments 10 and 11) for example, the speed limit for tracking three targets was significantly lower than for tracking two targets, and speed limit for one target was substantially higher than for two targets. In the four-target experiments (Experiments 5 and 6), the tracking performance for four targets was significantly worse than when tracking two targets in separate visual hemifields. For other experiments (Experiments 1, 1b, 3, 4, 7, and 9) that contrasted one target with two targets, the speed limit substantially decreased with the additional target. These results rejected the FINST model prediction.

Results were consistent with the FLEX theory proposed by Alvarez and Franconeri (2007), which is a resource theory of object tracking. The FLEX resource theory proposes that the resource is continuous rather than comprising discrete slots. Unlike FINSTs, there is no set limit on the number of FLEXs that can be deployed. Instead, it is assumed that there is a limited mental resource that is shared by all FLEXs. The more objects to be simultaneously tracked the less resource each FLEX receives. As the amount of resource allocated to each FLEX decreases, the maximum target speed for each FLEX decreases. Many studies documented trade-offs between speed and number of objects that can be tracked (Bettencourt & Somers, 2009; Liu et al., 2005). They interpreted their results as supporting the theory that speed and number of targets both draw on a common resource. However, spatial interference

between targets might confound their results. When targets move faster, spatial interferences between targets might occur more. All experiments in this thesis further exclude the confound of spatial interference and support the FLEX theory that each target receives less amount of resource when more targets are tracked.

However, Chapter 4 pointed out that a modified slots theory (Zhang & Luck, 2008), where each target can be allocated more than one slot, might be accommodated with our results of differential resource allocation. Under such a model, resource might be differentially allocated—faster targets could be allocated more slots than slower targets. But this modified slots theory can only account for tracking fewer than four targets. Horowitz and Cohen (2010) already demonstrated that the FLEX theory fits better than the modified slots theory for reports of the motion direction of tracked targets when the number of tracked targets is above four targets. However, this left open the issue of whether other information used in MOT besides motion direction is also fit better by FLEX theory. Future studies might ask observers to track more than four targets to distinguish whether the modified slots theory is worse than the FLEX theory according to our paradigm.

Besides spatial interference, attention switching, and FINST models, various other theories are also inconsistent with our results. For example, Yantis (1992) proposed that when tracking multiple objects, observers spontaneously group all tracked targets into a single virtual polygon, which each vertex represents a target. The ability to maintain formed groups of targets during tracking is the critical successful element. In the Yantis (1992)'s grouping theory, no matter how many targets participants were tracked, they were able to track multiple objects accurately when the targets appeared in easily grouped configuration, such as triangle, regular diamond, and pentagon, or when the targets were presented simultaneously not sequentially. According to Yantis (1992)'s theory, tracking three targets



might yield better performance than tracking two or one targets, which was totally contrary to our findings in all experiments.

The Model Of Multiple Identity Tracking (Oksama & Hyona, 2008) and the “object files” model (Kahneman, Treisman, & Gibbs, 1992) both are not appropriate to explain the results of this thesis, whose mainly emphasized on the dynamic bindings between identity information and location information. The information of target location and target identity were separately derived from the analysis of dynamic visual inputs with “where” and “what” system during the tracking period. MOMIT suggested the efficacy of tracking multiple objects depends on continuous serial activating and refreshing of the dynamic identity-location bindings with attention, and communications between the visual-spatial short-term memory (VSTM) and attention. In contrast, the “object files” model encoded the identity-location binding with multifocal attention at the start of the trial and maintained the binding throughout the trial. From the previous section of *rejecting the central bottleneck theory*, the hemisphere-independence evidence in our experiments already excluded a single focus attention model, so that MOMIT was also inconsistent with our findings. Although the “object files” model operated attention in multiple foci and performance substantially declined as the number of targets increased during encoding the identity-location binding, it was still difficult to reconcile our results with the object files model. After encoding the identity-location binding, the “object files” function should not influence tracking performance. Thus, the “object files” function must not contribute for the speed limit because all experiments in this thesis have 0.7 seconds to encode the identity-location binding regardless of fast and slow speeds.

In short, our results support the theory that object tracking is mediated by a flexible tracking resource, with less resource allocated to each target when more targets need to be tracked. The flexible resource allocation not only influences how humans dynamically select

multiple moving objects but also influences how humans to select multiple static objects. For example, when two visual objects are presented simultaneously and briefly, typically reporting visual properties of both is more difficult than only reporting the properties of either one alone (Alvarez et al., 2005; Duncan et al., 1994). The unattended stimulus may be missed because less or no attentional resource is allocated to it. For example, while talking with someone on a cell phone during driving, the driver is easily missing a traffic light or traffic signs (Strayer & Johnston, 2001).

Another core function of attention is modulation. Different from attentional selection, modulation determines how well the target information is processed after the target is selected from competing options (Chun, Golomb, & Turk-Browne, 2011). The limited resource is divided according to how many target to be selected, and then the amount of resource per selected target determines how well humans perform the attentional modulation. With regard to our tracking results, attentional modulation decides how fast human beings can track targets after the tracking resource is divided among targets by attentional selection.

If resource allocation is flexible, resource will be allocated to targets not only depending on how many targets are tracked, but also can be differentially allocated to targets so that some targets receive more resource than others. In Chapters 2 and 3, we demonstrated the allocation of tracking resource depends on how many targets we simultaneously tracked, with more resource allocated to each target when observers have to track fewer targets. In these situations, targets moved with equal speeds.

To understand whether tracking resource can be differentially allocated to targets, Chapter 4 asked observers to track two targets moving with different speeds. Our Experiments 8 and 9 showed that tracking resource could be differentially allocated between targets, with a faster target receiving more resource than a slower one. In particular when targets were both in the same hemifield, pairing a target with a slower target rather than one

of the same speed yielded a higher tracking speed limit for the critical target. The significant increment in speed limit of the critical target is probably because the slower target consumes less resource than each target in the same-speed condition and leads to more resource available for the critical target.

However, the ability to differentially allocate resources between targets with different speeds may have some limitations. Our Experiment 9 found evidence that resource allocation did not change during the trial despite variation of which target was faster during a trial. However, other researchers found that the resource allocation can be changed during the tracking period when the number of targets is varied (Drew et al., 2012; Ericson & Christensen, 2012; Wolfe et al., 2007). As we discussed in Chapter 4, the resource reallocation between targets during the tracking period might result from the explicit cues that helps observers to reallocate their attention to the new target set. In the future, cues could be added to our design of Experiment 9 to investigate whether resource can be reallocated between targets when the target speeds change during the tracking period. Another possible explanation is that humans are very bad at detecting speed change (McBeath et al., 1995; Traszczut et al., 2012). To facilitate resource reallocation among targets according to speed change during the trail, the future study can enlarge the extent of speed change.

In dual-task paradigms researchers have also investigated whether participants can allocate resource in different proportions. The issue is relative performance in two tasks, which is analogous to the tracking issue of relative performance for two targets. Several dual-task experiments also demonstrated an increase in performance of one task decreases the accuracy of the other, and this trade-off can be flexibly adjusted by experimenter's emphasized instructions and observers' intentions (Morey et al., 2011; Pastukhov et al., 2009; Sperling & Melchner, 1978; Tombu & Seiffert, 2008). But to our knowledge our experiments are the first empirical evidence to support the differential resource allocation between targets,

and that this allocation is based on two independent hemisphere-specific resources. We are not aware of previous dual-task experiments investigating whether differential resource allocation among tasks is hemifield-specific. Establishing whether the differentially allocable resource in those tasks is hemifield-specific would be one test of whether it is the same resource as that used for tracking.

The differential resource allocation might also be possible across different modalities. Allocating more attentional resource to visual stimuli can enhance visual discrimination and activate the relevant retinotopic visual cortex (Tootell et al., 1998). Allocating more resource to audition can allow listeners to detect finer sounds and to make finer discriminations between pitch differences (Woldorff et al., 1993). This differential resource allocation can also influence the flexible modulation of the spatial-based, feature-based, and object-based attention. The modulation of the relevant target depends on how much resource is allocated on it. When more resource are allocated to a specific location, feature, or object, the processing on attentional focus will be enhanced, leading to a better performance than another location, feature, or object that allocated less resource (Chun et al., 2011).

To conclude, from the above discussions, the resource theory is the best explanation for our findings that performance substantially drops as the number of tracked targets increases, and the tracking resource is differentially allocated among targets differing in moving speeds. The cross-talk model is excluded by eliminating the possible confound of spatial interference between targets or targets and distractors. Processing with one central bottleneck cannot explain why the tracking performance is better when targets are presented in separate hemifields than in the same hemifield.

Our results are unable to distinguish the serial account from the parallel account for tracking multiple targets within one single hemifield. Less resource allocated to each target (parallel account) and shorter time to update the target position (serial account) both are able

to interpret the significant cost on speed limits within a hemifield when the number of tracked targets increased. In my thesis, the serial theory of tracking targets within one hemifield is similar to the modified bottleneck model (dual-bottleneck theory) in the dual-task experiments. Thus, the two hemisphere-specific bottleneck model as well as the flexible resource theory works for track multiple objects within a hemifield.

Several recent works supporting resource theory on multiple object tracking documented that it was more difficult to track objects when objects moved at faster speeds (Alvarez & Franconeri, 2007; Liu et al., 2005) and when more objects needed to be tracked (Bettencourt & Somers, 2009). The present thesis provides evidence that excludes the confound of the spatial interference and speed effects, and demonstrates that allocation of tracking resource between targets depends on speed. Furthermore, we discovered that temporal resolution limits tracking to a greater degree with more targets. The temporal resolution for tracking each target is determined by how much resource is allocated to that target. The following section will discuss this relationship.

## **6.2 Tracking Resource per Target Determines Temporal Resolution**

This thesis investigated, for the first time, whether the temporal frequency limit on tracking, not only the speed limit, is set by the amount of processing resource available for each target. Previously published literature on tracking focused on explaining the effects of target number on speed and spacing effects (Alvarez & Franconeri, 2007; Bettencourt & Somers, 2009; Franconeri et al., 2010; Franconeri et al., 2008; Vul et al., 2009) rather than temporal resolution. Our Experiments 10 and 11 were performed to investigate the effect of additional targets on the temporal frequency limit as well as the speed limit. Both experiments demonstrated that temporal frequency was also the primary constraint on tracking performance, and that the temporal frequency limit decreases dramatically with the number of targets. Spatial interference appeared to have little effect, so apparently temporal

resolution for each target was determined by the amount of resource received. With regard to parallel tracking theories like flexible resource theory (Alvarez & Franconeri, 2007), a decline in the temporal frequency limit indicates that the temporal integration interval or temporal imprecision of the target representation increased.

For tracking one target, the constraints on performance were a 1.7 rps speed limit and ~7 Hz temporal frequency limit. Verstraten et al. (2000) also tested one target and found a similar result. Tracking was not possible above either the speed or the temporal frequency limit. This temporal frequency limit for tracking one target is similar to results of other high-level attentive temporal tasks, such as a 8-10 Hz limit of discriminating apparent motion from unmoving flicker (Battelli et al., 2001) or a 9-11 Hz limit of judging the relative phase of spatially separated flickering stimuli (Aghdaee & Cavanagh, 2007). It suggests that the temporal limits of object tracking are caused by central attentive processing. Central processing has a slower temporal frequency limit (3-7 Hz) than processing in early stages of vision (>30 Hz), such as flicker perception or first-order motion perception (Holcombe, 2009). The central processing plays a critical role in the selection of targets from surrounding distractors in the timeline.

Another possible explanation for the ~7Hz limit for tracking one target is that attention acts like a “blinking spotlight” (VanRullen, Carlson, & Cavanagh, 2007) that samples information periodically, even when not switching attention among multiple targets. Every 142ms, our visual system samples the current spatial information of objects during the motion period and determines the target that is closest to the target’s previously registered position. When the distractor comes into that position at the sampling time, observers must recognize the distractor as the target and this tracking event fails.

From this thesis, we further provide evidence of high-level processing in that attentional resource demands also limited temporal resolution of object tracking. Our Chapter

5 found that the temporal frequency limit dropped to ~4 Hz for tracking two targets and to ~2.6 Hz for tracking three targets. When central attentive processing need to deal with more than one target or attribute, the limited temporal resolution decreases significantly owing to less resource allocated to each target or attribute. Our 4 Hz limit for processing two targets is compatible with some other attentive temporal tasks, such as the cross-attribute binding task (Fujisaki & Nishida, 2010; Holcombe & Cavanagh, 2001). In this task, observers were required to judge which two features were presented simultaneously when each sequence was a repetitive alternation of two attributes values (Fujisaki & Nishida, 2010). For example, monitoring a patch alternating between red and green and an adjacent grating alternating between leftward tilted and rightward tilted, and then judge whether the rightward-tilted patch is synchronous with the red or with the green. When the alternating rate of these two cross-attribute stimuli is above 2-3 Hz, observers are unable to bind which two features were presented simultaneously. Fujisaki and Nishida (2010) interpreted the temporal limit for binding two features as suggesting that humans separately process “when” and “what” in the our brain, and then bind outputs from the “when” processing with those from “what” processing by central attentive processing. When less resource is allocated to central attentive processing for each target, performance of binding “what” processing with “when” processing deteriorates, leading to lower temporal limits. For our tracking results, observers separately process issues of “when” and “where”, instead of “when” and “what”. Central attentive processing might be responsible for binding the “when” processing with “where” processing for each target. Therefore, temporal limits on tracking performance might reflect a similar processing mechanism to that limits temporal resolution in the attentional binding tasks, with higher temporal limits for each attribute or target as more resource is allocated on it.

The different cortical networks mediating spatial versus temporal resolution of attention have been documented in a series of studies by Battelli and colleagues (Battelli et al., 2001; Battelli et al., 2003; Battelli et al., 2007; Battelli et al., 2008). Their patients with right parietal damage had poor temporal resolution in both the right and left visual hemifields whereas they only have worse spatial resolution in the contralateral visual hemifield. However, patients with left parietal lesion did not have lower temporal processing rates but had worse spatial processing in the right visual hemifield. They concluded on the basis of this and other evidence that the right hemisphere contains the “when” pathway responsible for processing the timing of events presented in either hemifield.

The spatial resolution might be proportional to the tracking speed limit, with the poorer spatial resolution leading to the lower speed limit. Intriligator and Cavanagh (2001) demonstrated that poor spatial resolution makes it difficult for observers to select targets from distractors, resulting in worse tracking performance. Successful tracking requires an accurate updating the current positions of targets, which is influenced by the spatial resolution. The tracking speed limit is also determined by how quickly observers can accurately update the current positions of targets. Thus, the lower speed limit results from inaccurate updating, which is influenced by the poor spatial resolution.

While Battelli et al. (2001) reporting that patients with right parietal lesion had substantially lower performance of MOT task in the left visual hemifield, testing with normal observers on object tracking in this thesis, no significant difference was found for tracking speed limit between right and left visual hemifield. In our Experiment 4, similar speed limits were found between right and left visual hemifields no matter whether observers were asked to track one or two targets. When monitoring eye movements to ensure accurate fixation in Experiment 6, we also found there was no significant difference in speed limit between two separate hemifields for tracking one target (Right:  $M=1.96$  rps; Left:  $M=1.93$  rps,  $t(5)$



=0.183,  $p=0.862$ , Cohen's  $d=0.076$ ) and two targets (Right:  $M=1.65$  rps; Left:  $M=1.61$  rps,  $t(5)=0.176$ ,  $p=0.867$ , Cohen's  $d=0.076$ ). Other hemisphere-specific experiments in this thesis also replicated those findings. Taken together with Battelli et al. (2001), the above findings suggest that for normal subjects spatial resolution is equally good in both visual hemifields.

The different mediating networks for spatial resolution and temporal resolution provide us a future research direction to confirm our suggestion that speed is the primary constraint for tracking one target with few distractors, whereas performance is mainly constrained by temporal resolution for tracking one target with many distractors. Similar to our hemisphere-specific paradigm in Chapter 3, two circular trajectories could be presented in separate hemifields, and the number of objects arrayed within each circular trajectory manipulated. Patients with right parietal lesion and normal observers could be recruited to track one target in the right or left hemifield, and measured their speed limits and temporal frequency limits.

According to the right-hemisphere “when” pathway theory, if the temporal frequency limit is reached, the temporal frequency limits in both hemifields should be equally lower for the patients than for the normal observers because the right parietal lobe underlies temporal attention in both left and right visual hemifields. On the contrary, with fewer distractors to avoid temporal frequency limit, the speed limit in the right hemifield should be higher than in the left hemifield for the patients, but not for normal observers, because the parietal network in the right hemisphere mediates spatial attention in the left visual hemifield. In other words, if there is significant difference on tracking performance between two hemifields, it must be caused by limited speed, not by limited temporal resolution, because spatial attention affects only the speed limit.

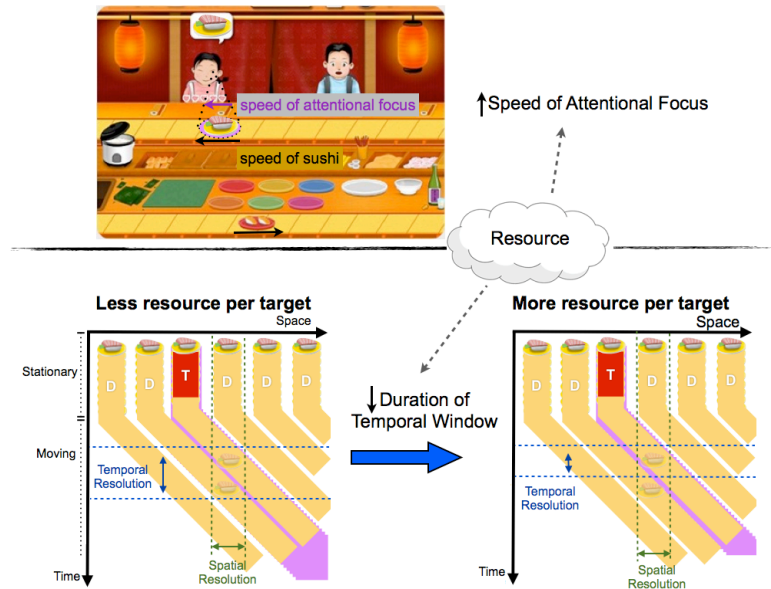
### **6.3 How does the Tracking Resource Mediate Tracking Performance?**

The core conclusion of the thesis is that the speed limit and temporal frequency limit decrease when each target is allocated less tracking resource. This resource theory can be thought of in terms of the sushi restaurant metaphor shown in Figure 6.1, which shows a girl paying attention to track her favourite sushi. In order to successfully track the sushi, the maximum speed of the attentional focus should be equal to or faster than the sushi. The more resource allocated to the attentional focus, the faster the girl can track the sushi. When more targets need to be tracked at the same time, she has less resource allocated to tracking each target, leading to lower speed limit (top of Figure 6.1).

With regard to the interpretation of temporal frequency limit, tracking resource determines the duration of the temporal window (temporal resolution) of the tracking focus. From the bottom of Figure 6.1, the space-time diagrams illustrate the relationship between temporal resolution and resource allocated per target. The less resource allocated to each target, the longer the duration of the temporal window (temporal imprecision) of each target. The longer duration of the temporal window, the more sushi trays will be selected at a given time. If there are two identical sushi trays selected at the same time, it is hard to distinguish which one is the tray the girl intends to track (left panel bottom). Increasing the resource allocation to that target shortens the duration of temporal window (as shown with the blue arrow at the bottom in Figure 6.1), leading to a higher temporal precision of that target. Here, the girl can accurately select her favourite sushi (right panel bottom). Therefore, a higher temporal frequency limit is found when each sushi tray is allocated more resource.

In short, tracking performance is determined by the speed of the tracking focus (speed limit) or the temporal resolution of attentional focus (temporal frequency limit). Both factors limit tracking performance, and the operating limitation depends on which one is reached firstly (see Chapter 5). But by what neural mechanism does lower resource allocation lead to

poorer speed limit and temporal frequency limit? In the following section, we will propose possible neural mechanisms for how resource allocation affects the speed of attentional focus and the duration of the temporal window.



**Figure 6.1. Cartoon representation of tracking resource mediating speed limits and temporal frequency limits**  
The speed of attentional focus is increased when more resource is allocated to it (top panel). Tracking resource is also able to shorten the duration of the temporal window (blue arrow, bottom panel). The temporal frequency limit is measured when the duration of temporal window is too long to distinguish these two sushi trays.

#### 6.4 The Neural Mechanisms of the Resource Allocation Effect on Speed Limit and Temporal Frequency Limit

Some functional magnetic resonance imaging (fMRI) studies suggest that the brain area underlying the capacity limitation of the MOT task is the posterior parietal cortex (Culham et al., 1998; Culham et al., 2001; Howe et al., 2009; Jovicich et al., 2001). The observed brain activity of the posterior parietal cortex increased with target load. Kojima and Suzuki (2010) further demonstrated that the amount of oxyhaemoglobin substantially increased in the parieto-occipital regions while paying more attention on the task. Therefore, the limited tracking resource might be mediated by the parietal cortex.

From above descriptions in section 6.1.1, our findings that less resource allocated to each target reduces speed limit and temporal frequency limits can be reconciled with the oscillatory neural network (Kazanovich & Borisyuk, 2006). Attending a target is mediated by

synchronous oscillations of central oscillators in frontal-parietal networks and peripheral oscillators in visual cortices. When a target moves, a new population of cortical neurons must join the synchronized assembly (synchrony) and the neurons representing the old location must leave the assembly (desynchrony). The synchrony and desynchrony take time to complete, and thus failure of tracking will occur if a distractor arrives at the former target location when those neurons are still partially synchronized (leading to a temporal frequency limit), and if a target moves faster than the rate at which new neurons can be synchronized (leading to a speed limit). Because the limited phase space, when more targets needed to be tracked at the same time, the angle between their phases decreases, increasing interferences so that they are less likely to maintain their coherent oscillation for the corresponding target only. Thus, this limited phase space leads to impose a speed limit and temporal frequency limit. The theory of oscillatory neural network claimed that tracking each target is mediated by only a specific phase space, and therefore it is hard to explain our findings of differential resource allocation between targets. For the sake of better explanation on differential resource allocation, the theory of oscillatory neural network should be modified so that each target (Kazanovich & Borisyuk, 2006) is allowed to be mediated by more than one specific phase.

The present thesis proposes another explanation for that a limited resource in the brain might be like a pool of neurons that can be flexibly assigned to the targets. As the number of tracked targets increases, the number of neurons assigned to each target decreases and reduces the precision of attentional resolution (i.e. temporal frequency limit) or the maximum speed of the tracking focus (i.e. speed limit). The following paragraphs will explain these two neural mechanisms of less resource leading to lower speed limit and temporal frequency limits.

The neural link between less resource allocated to each target and poorer speed limit of the tracking focus is now described. Each neuron of the parietal cortex has a spatially

restricted receptive field. Successful tracking a target moving across the visual field requires consecutive recruitment of new neurons and dropping of old neurons of the parietal cortex. If the target moves faster than the rate at which new neurons can be activated, observers would fail to track the target. With fewer neurons involved in this process of recruitment, there was no neuron recruited as the new neurons before the old neurons are entirely released, leading to tracking failure at fast speeds. According to the resource theory, the number of neurons assigned to each target decreased as the number of simultaneously tracked targets increased. Thus, less resource allocated to each target results in lower speed limits of tracking focus. This also explains our findings of that tracking resource can be differentially allocated to targets with distinct speeds. Human can distribute different amount of neurons to targets with different speeds, with the fast-moving target receiving more neurons than the slow-moving target. Relative to one of two targets with equal speeds, the fast-moving target in the fast-slow condition has more neurons available to be recruited for successful tracking at faster speeds, leading to a higher speed limit.

The amount of neurons distributed among targets could explain why less resource allocation to each target reduced the temporal precision of attentional resolution. Previous studies demonstrated that more attention involved could shrink neuronal receptive fields around the attended stimulus and improve the selectivity of the neuron (Moran & Desimone, 1985; Spitzer, Desimone, & Moran, 1988). Following this logic, more resource allocated to each target might also reduce the duration of the temporal window (increase the temporal resolution). From previous descriptions, tracking a target moving from location A to location B, attentional resources were reallocated to activate the neurons corresponding to the receptive field of location B and drop the neurons corresponding to the receptive field of location A. It took time to complete this process of the resource reallocation, and here the duration was termed as the duration of temporal window. More resource allocated to the

tracked target could shorten the duration of resource reallocation (sharpen the duration of temporal window). If a distractor behind the tracked target moved fast enough to come into the temporal window, observers would mistake the distractor for the target. In other words, tracking failures occur when a distractor behind the target came into the receptive field of location A faster than the neurons finished the process of the dropping. Thus, less resource allocated to each target enlarged the duration of the temporal window and then led to lower temporal frequency limits.

But why do fewer numbers of neurons allocated to each tracked target induce higher brain activity (or CDA amplitudes in the next section) of the parietal cortex (Culham et al., 1998; Culham et al., 2001; Howe et al., 2009; Jovicich et al., 2001)? One assumption should be proposed to address this issue. When tracking a target in a very easy condition (ie. very slow speeds), the entire pool of neurons is not allocated to the target, so some neurons are left idle. When the condition becomes difficult (ie. increasing the speeds or target numbers), more neurons are recruited for meeting the demands of difficulty. Therefore, as the number of tracked targets increases, the total number of activated neurons increases although the percentage of neurons assigned to each target decreases, leading to higher brain activity (or higher CDA amplitudes).

### **6.5 Resource Theory in Multiple Object Tracking: An Electrophysiological View**

Although neuroimaging studies indicate posterior parietal cortex has load-dependent activation (Culham et al., 1998; Culham et al., 2001; Howe et al., 2009; Jovicich et al., 2001), the studies did not disambiguate whether the activation results from consuming more tracking resource or to attending more objects during the target selection period. They did not clearly rule out that the observed brain activity corresponded to the target selection period. In an ERP study however, Drew and Vogel (2008) isolated neural measures of target selection and sustained attention processes that underlie tracking. In their study, participants performed a

MOT task with a bilateral array, such as 8 objects in each hemifield, and participants tracked a subset of targets in one single hemifield. Drew and Vogel (2008) found a transient contralateral negative wave (N2pc wave) about 200-300ms after the cuing stimulus during the target selection phase, in which observers select targets among distractors. Three hundred milliseconds after motion onset, a large sustained contralateral negative wave during attentive tracking (the contralateral delay activity; CDA) was observed over posterior parietal electrodes. The amplitude of both waves was substantially higher for tracking three targets than for tracking one target (Drew et al., 2012; Drew & Vogel, 2008). Drew et al. (2012) further documented that the CDA amplitude is an online sensitive index that dynamically reflects the number of tracked targets: changes in the CDA amplitude were associated with both the increment and decrement of the target set.

Although the CDA amplitude is not an appropriate index to reflect the difficulty of the tracking task (Drew, Horowitz, & Vogel, 2013), it might support the resource theory of object tracking. The behavioural data of Drew et al. (2013) showed increasing either speed or target load substantially decreased tracking performance, but for tracking one target, there was no significant speed effect on the CDA amplitude. They suggested the CDA amplitude only reflected the target load but were not associated with the variation of speed. However, the failure to reflect the speed effect on the CDA amplitude might be because the speed they manipulated (2.2 deg/s and 3.8 deg/s) was not fast enough to reduce the CDA amplitude. According to our experiments, tracking performance usually deteriorated as the speed increased above 12 deg/s (1 rps). Thus, a speed effect on the CDA amplitude might be apparent if we test with higher tracking speeds in future studies. Furthermore, the reason for the non-significant speed effect on the CDA amplitude for tracking one target in Drew et al. (2013) might be that the fast speed they used was not fast enough to exhaust 100% of

resource, and therefore the intensity of neural activation is similar to the slow-speed condition, leading to equal CDA amplitude between two conditions.

For tracking three targets, the CDA amplitude in the fast-speed condition was significantly lower than in the slow-speed condition (Drew et al., 2013). They suggested that increasing speed appears to increase the probability of dropping targets, as the CDA amplitude is a sensitive index to reflect the size of the target set. This result provides some electrophysiological support for our conclusion that the number of tracked targets and the tracking speed share the same attentional tracking resource, with higher tracking speed leading to fewer targets being able to be tracked. When tracking three targets with fast speeds, observers might drop one and reallocate resource between two targets, resulting in the amount of resource in each of two targets increasing from 33% to 50%, and therefore the CDA amplitude corresponds to the change of resource allocation. To strengthen our conclusion that both the number of tracked targets and speed share the same resource, measuring the CDA amplitude might be one approach to explore the neural mechanisms underlying resource allocation depending on speed change.

Drew et al. (2013) also demonstrated that spatial interference and number of tracked targets did not share the same tracking resource. In their study, the number of distractors was manipulated, and they suggested that worse performance with distractor load is caused by participants tracking the distractors when they confused targets with distractors. This was shown in their CDA amplitude, on which only target load had a significant main effect, whereas there was no effect of distractor load. However, their behavioural data showed both target load and distractor load have substantial effects on tracking performance. In addition, there was no significant interaction between target load and distractor load. It indirectly supported that the spatial interference and number of tracked targets independently influenced tracking performance but did not share the same resource.



An alternative possible experiment design might be able to investigate whether tracking resource can be reallocated among targets, based on the opinion of Drew et al. (2013) that CDA amplitude is only sensitive to detecting variation of target load rather than variation of speed. Modifying the paradigm from our Chapter 4, observers could be asked to track three targets in two conditions: an equally-fast speed (EFS) condition or a differential speed (DS) condition, with one moving very fast and two moving very slow. In the EFS condition, each target would start tracking with 33% of the resource; after few seconds tracking, each of two targets increases in amount of the resource received from 33% to 50%. This is because it is too hard to simultaneously track three fast-moving targets, and observers drop one target as well as reallocate the resource from that target to another two targets. In this case, the CDA amplitude of the EFS condition would decrease owing to the decrement of the target set or according to our assumption that CDA amplitude corresponds to the amount of resource allocated to each target. In contrast, in the DS condition, during the tracking period, no target is dropped because observers can simultaneously track one fast-moving target and two slow-moving targets. Thus, no change on the CDA amplitude would be found because there is no resource reallocation among targets.

## **6.6 Conclusion**

Tracking multiple moving objects is mediated by a mental tracking resource composed of two independent hemisphere-specific resources. The present thesis supports this claim by avoiding the confound of spatial interference and providing evidence that the tracking resource can be differentially allocated between targets. Both speed limits and temporal frequency limits decline with increases in the number of tracked targets, indicating each target received less tracking resource. Performance is constrained by the speed at which the tracking focus can move, and by its temporal resolution. More resource allocated to the target improves temporal resolution, and possibly the speed limit.

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## PARTICIPANT CONSENT FORM

Project: **Position Perception, attention, and object motion**

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- 1 I, ..... (name), agree to participate in the study described in the Participant Information Statement attached to this form.
- 2 I acknowledge that I have read the Participant Information Statement, which explains the aims of the study and the nature of the investigation, and the statement has been explained to me to my satisfaction.
- 3 I understand that I can withdraw from the study at any time.
- 4 I agree that research data gathered from the results of the study may be published provided that I am not identified.
- 5 I understand that if I have any questions relating to my participation in this research, I may contact Dr Alex Holcombe at 02 9351 2883, [alexh@psych.usyd.edu.au](mailto:alexh@psych.usyd.edu.au)
- 6 I acknowledge receipt of a copy of the Participant Information Statement.

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Signature of Participant

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Date

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Please PRINT name

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Signature of Investigator

Any person with concerns or a complaint about the conduct of the study may contact Marietta Coutinho, Deputy Manager, Human Ethics Administration, University of Sydney on (02) 8627-8176 (Telephone); or [mcoutinho@usyd.edu.au](mailto:mcoutinho@usyd.edu.au) (Email)



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