The Interdependence of Attention, Memory, and Performance Based Reward

by

Christie Haskell

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Abstract

Attention is frequently described as a distinct process with distinct effects, and many researchers have suggested that it has a distinct place in the brain. And yet attention is necessarily entangled with the systems required to complete experimental tasks. Perceptual experiments entangle attentional effects with the properties of perceptual neurons, experiments with transient stimuli entangle the effects of memory with attention, and the early experiments on attention in primates entangled the effects of attention and reward. The purpose of the present thesis, therefore, was to disentangle the effects of attention from the effects of memory and reward on orientation judgements across ten experiments. In all experiments, participants were required to make an orientation judgement from memory of a grating (Chapter 2) or Gabor (Chapters 3 & 4) that appeared briefly on the display. Chapter 2 presents five experiments combining a manipulation of spatial attention using an exogenous luminance cue that was 100%, 80%, or 50% valid with a manipulation of memory consolidation using sequential and simultaneous presentation of two circular gratings. Valid cuing improved performance only when two stimuli appeared together and improved it to the level of performance on uncued sequential trials, whereas invalid cueing always reduced performance. Further, mixture model fitting results indicated that non-predictive cues improved performance by reducing guessing and predictive cues improved performance by increasing precision. These results suggest that, when the demand on

memory is greater than a single stimulus, attention is a bottom-up process that prioritizes stimuli for consolidation, thus attention and memory are dependent and synergistic, and that the mechanism by which spatial attention affects precision may be dependent on how we implicitly monitor our environment for statistical regularities. Predictive cues communicate importance about a spatial location and reward is another mechanism that communicates importance, and this is what motivated the experiments presented in Chapter 3. Chapter 3 presents four experiments combining a manipulation of spatial attention via a 50% valid luminance cue with a manipulation of performance-based reward that was communicated to participants by either sound, time, or points. The reward received could be either finely or coarsely related to participant errors and this was manipulated between subjects. Sound and time were ineffective at communicating the reward distribution, but when participants were awarded points, valid cuing improved performance and kurtosis was increased on valid trials only when rewards were finely related to their performance suggesting a dependent relation between reward and attention. One explanation for these results is that reward increases vigilance and attention increases visual search efficiency. The experiment presented in Chapter 4 evaluates this hypothesis. Viewing time was fixed by requiring participants to fixate at the target location to control its offset. We found that under these conditions the effects of cueing and reward were eliminated. Taken together, these results provide evidence that it is not possible to fully disentangle the effects

of attention from the system(s) used to perform the task suggesting that spatial attention is not a separate mechanism unto itself, but a property of perception.

Acknowledgements

During the writing of this thesis I reflected frequently on the people that made it possible.

Three years into my career in engineering it was becoming obvious that my expectations about what I wanted out of my engineering career and my reality did not intersect. I started taking online courses at the University of Waterloo in Psychology in parallel with continuing to work in engineering to explore what had always been a secondary interest: thinking about thinking. It was while taking Physiological Psychology, which was facilitated that term by Dr. Britt Anderson, that my enthusiasm for Psychology really took off. It seems fitting that my graduate journey in Psychology both started and ended with the same person.

Originally I was going to start by doing another undergraduate degree, this time in Psychology. It had not occurred to me to consider applying directly to graduate school, but following the advice and support of Dr. Jeffrey Yokota, my Flight Mechanics, Fluid Mechanics, and Propulsion undergraduate professor, I decided to apply with only two weeks remaining until the application deadline. I only applied to the University of Waterloo, and exceeding my expectations, I was accepted.

The journey since has not been easy. I started behind. Technical writing and scientific writing are not equivalent, and while I was trained in the former I was not trained in the latter. I was behind my peers in my scientific writing ability. I had also read few scientific articles before. Doing so is not a common experience of engineering students where the training is specifically tailored towards an industrial career. As such, I had no prior education about what a graduate student in Psychology, or a graduate student in general really, might do to prepare for an academic career, something that undergraduates in Psychology are frequently taught. But above all else, I had less time to really consider what I was interested in studying and the result was that I stumbled through my first three years without much real direction. I received a lot of advice and support during those three years from a lot of different people that made my Master's degree possible, most notably: Dr. Jennifer Stolz, Dr. Serje Robidoux, Dr. Stephanie Waechter, Dr. Nathaniel Barr, Dr. Sana Rizvi, Amanda Pogue and Marg Ingleton.

It was after the completion of my Master's thesis that I approached Dr. Britt Anderson with a proposal for not only working together, but for finishing the Ph.D. in two years. And he accepted the challenge. The journey working with Dr. Anderson has been incredible. It had everything you might expect a journey to have, peaks and valleys, obstacles, dead ends, and he pushed through them with me at an accelerated pace despite the risk. He believed in my abilities when I was not sure I believed in them myself. And we did it. In just a little over two years from the start of our journey together the data was collected and I was employed in a career our work together so uniquely prepared me for it's rather incredible.

There are people who I am sure will disagree, but to me the most important thing an academic professor does is mentor students. The relationship between an academic advisor and his or her student can really make or break the success of a graduate student. And yet professors are not taught how to mentor and are left to figure that out on their own. The success of Dr. Britt Anderson's students speaks for itself. When it comes to mentoring, he excels. Without the advice and support of Dr. Anderson, this thesis would not have been possible.

I would also like to give special thanks to Dr. Jay Michela with whom I worked on a side project for most of my time at the University of Waterloo and from whom I also received immeasurable advice and support.

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Dedication

This thesis would not have been possible without the love and support of my partner Jordan Marsh, my best friend Miranda McEwin, and especially my father Gary Haskell. You have always been there to support me and offer advice, even when my decisions did not make sense to you or you did not agree with them. There is no one I can count on more than you, even if it is three am and the spider is less than a centimeter long (notable mention to Jordan for his war with the wasps). I could not ask for a more loving and supportive Dad and I would not have achieved what I have and grown up to be who I am if it were not for your wisdom, care, and truly unconditional love.

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Chapter 1

General Introduction

Attention is frequently described as a distinct process with distinct effects, and many researchers have suggested that it has a distinct place in the brain. And yet attention is necessarily entangled with the systems required to complete experimental tasks. Perceptual experiments entangle attentional effects with the properties of perceptual neurons, experiments with transient stimuli entangle the effects of memory with attention, and the early experiments on attention in primates entangled the effects of attention and reward. So, when reports of such experiments describe the results as attentional in nature how do we know what was "attentional" as opposed to what was perceptual or otherwise. As a result, the word "attention" has been employed as a tool of mass explanation for a wide variety of experimental observations collected during a variety of tasks and contexts. Decades later, this variety has resulted in the division and sub-division of attention into a corpus of processes that are contextually deployed, and while we travel further down the rabbit hole of increasingly subtle manipulations we are still left with the same vaguely defined mechanism of attention that we started with. The field of attention in Cognitive Psychology therefore is not unlike the opposite of the metaphor of the blind persons grasping at the elephant. Where they individually conclude that they are touching different things, we observe varying results and label them all attention.

A famous quote by William James (1890) starts by stating that ”Everyone knows what attention is...” and yet 136 years later there really is not a lot of consensus about attention. For every attention researcher you ask you will get a different answer, and consequently it has been described using a wide variety of terms and metaphors (Fig. 1.1). Much of the difficulty in defining attention rests in its context dependence, and it is here that this thesis approaches studying it. Over a set of ten experiments, this thesis demonstrates that what has traditionally been classified as an independent mechanism of attention is not independent, but rather is dependent on the systems employed to complete the tasks. Further, we demonstrate that the effects of spatial cueing, effects known to be incredibly robust, arise for different reasons that are context dependent and can even be eliminated under certain conditions.

Figure 1.1: Word cloud of terms historically used to describe attention.

The focus of this investigation was narrowed to two domains: memory and reward. Memory systems have traditionally included attentional components and reward effects have traditionally been described as effects on attention. The experiments presented in this thesis therefore combine memory manipulations with attention manipulations, and reward manipulations with attention manipulations in order to address the independence or dependence of attention with memory and reward systems. As such, the introduction is divided into three main parts. The first part provides a brief overview of the early work done on the effects of attention on perception. The second part discusses experiments with transient stimuli that require memory for reports. Finally, the third part provides an overview of research on the effects of reward on visual perception.

1.1 Attention

The study of attention has a long history. It interested scholars well before psychology emerged as a discipline. For instance, in 1538, philosopher Joan Luis Vives noted the role of attention on the formation of memories (D. J. Murray & Ross, 1982), and in 1714, philosopher Gottfriend Leibniz suggested that "attention is a determination of the soul to know something in preference to other things" (Leibniz, 1989). Most famous is philosopher William James's (1890) views on attention that "it is a taking possession by the mind, in clear and vivid form, of one of what seem several simultaneously possible objects or trains of thought". Thanks in part to Wilhelm Wundt's development of an experimental psychology lab in the 1880s, today such ideas are not left only to the whims of philosophers alone, but are also scientifically testable.

Many of the early studies on attention used auditory tasks like the dichotic listening task. In one such experiment, Cherry (1953) presented a different message to each ear via headphones and had participants repeat out loud the message from one of the ears as accurately as possible. He found that while participants could notice physical differences between the messages, such as sex or language, they were unable to recall any specific words from the unattended message. Furthermore, if the physical features were similar between the two messages the task became more difficult. Results from these dichotic listening experiments culminated in the first model of attention, Broadbent's (1958) Filter Theory. The model consisted of a sensory store akin to short-term memory and a sensory filter that selected items from the sensory store for further processing.

In the early 1960s, information processing theories became dominant in Cognitive Psychology, and with it came a shift from studying attention using auditory tasks to studying it with visual tasks. It was during this time that Stroop's (1935) earlier work on the Stroop effect was rediscovered and the Colour-Word task became widely used as a method of studying attentional and linguistic processes (reviewed in MacLeod, 1991). The Colour-Word task involved participants having to indicate the font colour of a colour word. The typical result was that when the font colour and colour word were the same responses were faster. One theory that arose from such work was that attention is a limited-capacity resource that results in interference in tasks like the Colour-Word task when different processes compete for resources (Kahneman, 1973).

Visual attention, the type of attention of interest here, has since been divided into three main 'units': object-based attention, feature-based attention, and spatial attention. Object-based attention is the selecting of discrete objects (reviewed in Scholl, 2001), whereas feature based attention is the selecting of discrete features of objects such as shape, size, or colour (reviewed in Carrasco, 2011). Spatial attention, the selecting of discrete regions in space and the main focus of this thesis, is the 'unit' of attention that has been the subject of most traditional models and metaphors of attention (e.g., spotlights and zoom lenses).

Spatial attention is divided into two categories: overt and covert. Overt spatial attention is the attending to a region in space by physically moving the eyes to look at that location, and covert spatial attention is the attending to a region in space that is different from where the eyes are fixated. Covert attention is further divided into two more categories: exogenous and endogenous. Exogenous spatial attention is an involuntary orienting to a region of space as the result of an abrupt visual change in that region such as a change in luminance. Exogenous attention is deployed quickly, but it also decays quickly (100 - 120 ms peak; Cheal, Lyon, & Hubbard, 1991; Ling & Carrasco, 2006; Müller & Rabbitt, 1989; Remington, Johnston, & Yantis, 1992). In contrast, endogenous attention is voluntary and reflects our ability to intentionally monitor a region of space. Endogenous attention is deployed more slowly (300ms; Mueller & Findlay, 1988), but it can be sustained. The experiments reported in this thesis use a manipulation of covert, exogenous spatial attention via an abrupt onset luminance cue; therefore, the remainder of this section will be in describing them. The final eye-tracking experiment presented in Chapter 4 mixes both overt and covert spatial attention, and so the former will be addressed in the introduction to Chapter 4.

1.1.1 Covert, exogenous spatial attention

A common procedure for manipulating spatial attention is to use an exogenous, spatial cue. The intuition is that such abrupt onset events involuntarily direct the attention of a participant to the cued spatial location. Posner's (1980) seminal work using central (endogenous) and peripheral (exogenous) cues to capture attention demonstrated that peripheral cues in the form of dots or bars that appear in potential target locations improved response time and accuracy when they appeared in the same location as the target, and hurt response time and accuracy when they appeared elsewhere. These early results have been replicated many times (reviewed in Carrasco, 2011). Several theories have been suggested to explain how exogenous, spatial cues improve performance on tasks involving targets in the attended locations such as: increased spatial resolution, noise exclusion and distractor suppression, uncertainty reduction, and probability. I will briefly describe these here.

Spatial resolution

It has been suggested that covert, spatial attention changes the appearance of stimuli appearing in attended locations by increasing the spatial resolution in the attended region (reviewed in Anton-Erxleben & Carrasco, 2013). Spatial resolution is not uniform across the visual field, it decreases from the center to the periphery (DeValois & DeValois, 1988). Consequently, response time and accuracy are improved for stimuli appearing at the center of the visual field (e.g., Carrasco, Evert, Chang, & Katz, 1995). Prior work has demonstrated performance improvements in attended regions on tasks that are mediated by spatial resolution. For example, one such task is the Landolt-square acuity task. A Landolt-square is a square with a small gap on one of its edges and participants are required to indicate on which edge the slit is located. One such experiment using this task demonstrated that the effect of eccentricity on performance was reduced for cued targets supporting the hypothesis that spatial attention increases spatial resolution (Yeshurun & Carrasco, 1999).

Noise Exclusion & Distractor Suppression

Another route through which spatial attention has been suggested to affect visual perception is noise reduction either by suppressing distractors or excluding background noise. The likelihood of one or the other is related to the context of the task so they are therefore not mutually exclusive. For instance, in one experiment, Shiu and Pashler (1994) presented participants with single digits that were pre-cued with a valid, invalid or neutral cue. Following the target, one or multiple masks appeared in target and non-target locations. They found that participants made the same amount of errors on valid trials when there were multiple and single masks, but made significantly more errors on invalid trials only when there were multiple masks implicating distractor suppression as the probable explanation for these performance differences. In another experiment, Lu, Lesmes, and Dosher (2002) paired central spatial cueing via arrows pointing to one of four corners with variable amounts of signal stimuli (1 or 4), external noise masked locations (1 or 4), boxes centered on stimulus locations (1 or 4), and the style of those boxes (flashed, elaborated or stationary). The signal frame was embedded between one noise frame and two noise frames. Participants were required to indicate the orientation of the pseudocharacter that was in the cued location on the signal frame. The cue was therefore 100% valid and endogenous. They found that performance (measured by contrast threshold) was largely the same across all display conditions suggesting that spatial attention served to filter out the signal unrelated noise.

Uncertainty Reduction

When multiple locations are possible, spatial attention may also have effects at the level of decisions by reducing uncertainty about the target location. This may occur in conjunction with the mechanisms previously discussed: there is less uncertainty about where a target may appear because irrelevant details in the background have been filtered out. For instance, Solomon, Nilli, and Morgan (1997) had participants indicate whether a target was higher or lower in contrast to three distractors of equal contrast and found that performance was improved when the target location was validly cued compared to uncued. These results are best explained by uncertainty reduction of the location of the target in the array.

Probability

The mechanisms discussed so far rely on the physical salience of the spatial cues; however, their effects may also be because they communicate information about a possible target. There is increasing evidence that spatial probabilities are one route by which cues influence perceptual judgements (Enns & Brodeur, 1989; Eriksen & Yeh, 1985; Johnson & Yantis, 1995; Jonides, 1980). Recently, Droll, Abbey, and Eckstein (2009) found that the cueing effect increased as the information available (via feedback) to learn the cue predictiveness also increased. Further, Druker and Anderson (2010) showed that people can learn spatial probabilities in the absence of such feedback, and that performance is improved for targets in probable locations. As well, Jiang, Swallow, Rosenbaum, and Herzig (2013) demonstrated using a visual search task that after a few dozen trials participants became biased towards the location where the target was most probable to appear, and that this bias persisted even when the context changed.

1.2 Transient stimuli

The early models of memory included integrated components for attention, but when information processing theories overtook them in the transition to Cognitive Psychology, discussions about the interaction between attention and memory systems faded. Even in cases where transient stimuli were used to study the mechanisms of attention, such as in some of the experiments reported above, discussions about memory systems are largely absent. In Carrasco's (2011) review "Visual attention: The last 25 years", the word memory is only mentioned twice. So, even in cases where attention experiments require memory the memory component is not manipulated and is largely ignored. Recently, experiments have begun to emerge that explicitly combine memory and attention manipulations and these are discussed in the introduction to Chapter 2. Here I will present the motivation behind the five experiments reported in Chapter 2.

Experiments that assess attentional effects with transient stimuli intermingle the effects of memory and attention making it difficult to apportion between them responsibility for any effects on response time and accuracy. Consequently, the results of many such experiments are typically described as attentional without mention of memory. Recent studies by Liu and Becker (2013) and B. Anderson and Druker (2013) indicated a way forward in that they essentially used the same procedures to examine memory and attentional processes. Liu and Becker (2013) investigated whether the increased amount of time taken to make a perceptual report of one of multiple stimuli in memory was the result of a serial bottle-neck or a resource limitation. Using a procedure adapted from work by Wilken and Ma (2004), their participants were presented with two types of trials (sequential and simultaneous) and were required to make an orientation judgement from memory. Liu and Becker (2013) fit a mixture model, originally developed by Zhang and Luck (2008), comprised of a von Mises function (akin to a normal distribution on the circle) and a uniform distribution to the distribution of errors. From the parameters of this mixture they estimated parameters for precision (standard deviation of the von Mises function), bias (mean of the von Mises function), and guessing probability (the mixing proportion for the uniform distribution). In their study, guessing was operationalized as the error of responses that were guesses falling on a uniform distribution, which is what you would expect to find if a participant on any given trial had failed to consolidate the stimulus into visual short-term memory and was forced to estimate was orientation it had been at. Liu and Becker (2013) found that accuracy was better on sequential trials than simultaneous trials, and that the accuracy improvement was associated with a decrease in the guessing probability without changes in the precision or bias parameters. Liu and Becker (2013) concluded that there was less frequent guessing on sequential trials and that this supported the hypothesis that consolidation of orientation information is serial.

In contrast, using a similar task but different analysis methods, B. Anderson and Druker (2013) reported that the improved accuracy for orientation judgments with exogenous cueing was due to an improvement in precision. A single Gabor appeared briefly on the display on either the left or right hand side of fixation and was preceded by a non-informative spatial cue consisting of a white box. Participants were required to estimate from memory what the orientation of the Gabor was by rotating a response line in the same location the Gabor appeared in. Precision was measured by the absolute value of the median error between the true orientation and the judged orientation.

The two tasks used different manipulations with otherwise very similar procedures so it became possible to envision combining the two tasks together to look for memory and attentional effects in a single task. The analysis methods of the experiments reported in Chapter 2 combine both procedures and analysis methods to allow a comparison between model-free (median absolute angular difference) and model-based (mixture model) precision. Through a set of five experiments we demonstrate that memory and spatial attention are necessarily entangled and suggest that some of what we call attention may in fact be a property of how we consolidate visual stimuli into short term memory and how we implicitly monitor our environment for statistical regularities.

1.3 Rewarded stimuli

Reward effects on visual perception parallel attentional effects. For instance, Hickey, Chelazzi, and Theeuwes (2010a) demonstrated that reward enhances the salience of visual objects even when doing so hurts performance. Participants were required to search for a unique target, which was identifiable based on its shape, among several homogenous distractors of a different shape and indicate the orientation of a small line in the interior of the target (vertical or horizontal). Most of the time one distractor was coloured differently than the rest of the objects on the display. Correct responses were rewarded with a randomly high or low monetary reward. Response times to targets that were of a colour associated with a high reward on the previous trial were fast, but were slow when a distractor was associated with the previously rewarded colour. Further, response times to targets that were the colour of a distractor that was previously associated with a suboptimal outcome were fast, and response times to targets that were of a colour associated with a low reward on the previous trial were slow.

Reward has also been shown to have effects similar to the effects of probability on attention (e.g., Jiang et al., 2013). Using a visual search task, Hickey, Chelazzi, and Theeuwes (2010b) demonstrated that when target selection resulted in reward, participants were biased to return to the target location and were biased away from locations that were occupied by salient, task-irrelevant distractors. Further, B. A. Anderson, Laurent, and Yantis (2011) demonstrated in a visual search task that inconspicuous distractors that were previously associated with a monetary reward slowed the search for salient targets. However, different from the fast and implicit effects observed for probability, it has been shown that reward effects are absent when they are not explicitly related to the task suggesting that reward effects may be goal-driven, but not implicit as the effects of attention are (Jiang, Sha, & Remington, 2015).

It is common in the reward literature investigating reward effects in visual perception tasks to describe results in terms of effects on attention; however, attention is not often explicitly manipulated in these studies. Rewards are also often discrete and associated with spatial locations or features. Less understood is how reward and attention affect visual perception when they are both manipulated in the same task and when the rewards are not discrete, but are performance-based and distributed variably across the distribution of errors. In the introduction to Chapter 3 a few studies where attention and reward have been manipulated together are described and the three experiments reported in Chapter 3 and one experiment in Chapter 4 use tasks where spatial attention and reward were both manipulated and rewards were based on performance, rather than locations or features. These performance based rewards allowed a continuous variation in the magnitude of the rewards based off of the participants performance rather than the typical static and discrete rewards used in most of the studies on reward. We demonstrate that variable performance-based rewards may interact with spatial attention, suggest that this may result from changes in vigilance and demonstrate that these effects can be eliminated when viewing time is fixed.

1.4 Purpose of the Thesis

Taken together, the purpose of this thesis was to evaluate the dependence or independence of the effects of attention in the context of memory and reward manipulations. We present ten experiments using an orientation judgment task in three chapters (2, 3 & 4) that assess whether some of the effects typically described as attention may not necessarily be attention, but are a property of the systems required to complete the tasks (i.e., memory and reward systems).

In Chapter 2, five experiments are presented where memory was manipulated via the presentation of two stimuli either sequentially or simultaneously and attention was manipulated via a spatial cue that was either 100%, 80% or 50% valid. In Chapter 3, four experiments that combine several performance-based reward signals that could be coarsely or finely related to performance with a non-predictive spatial cue are reported. Finally, Chapter 4 presents an experiment that combined the methods from the experiments in

Chapter 3 with gaze-contingent methods in order to evaluate whether processing time mediated the effects reported in Chapter 3, Experiments 3 and 4.

A discussion about alternatives to understanding attention suggested by the results of the ten experiments reported is provided in the General Discussion.

Chapter 2

Memory and attention interact to affect response precision

This chapter is largely a reproduction of the manuscript Haskell and Anderson (2016).

2.1 Introduction

The purpose of the present experiments was to investigate the effects of spatial attention and memory on performance when memory and spatial attention were manipulated in the same task. Traditionally, memory and attention experiments have used different experimental methods and different analytic tools. As a result, attention experiments that mimic memory procedures and ask participants for their responses after stimuli have disappeared, as in the present experiments, are only now beginning to emerge. For instance, Sergent et al. (2013) were interested in investigating the interaction between attention and memory using post-cues. They found that orientation judgements were improved when spatial attention was oriented to the location previously occupied by a Gabor, demonstrating that post-cued attention can serve to revive a stimulus in memory that might otherwise have been lost. Further, A. M. Murray, Nobre, Clark, Cravo, and Stokes (2013) demonstrated this effect using multiple stimuli. Participants were required to report the orientation of one of four arrows, and the proportion of responses correct was highest when the location of the target arrow was post-cued before participants were prompted to respond.

A recent study using pre-cues by Pack, Klein, and Carney (2014) provided evidence that signal enhancement and spatial uncertainty reduction, attentional theories that are strictly perceptual, were insufficient to explain cueing effects of transient stimuli (see also Cameron, Tai, & Carrasco, 2002). Following a non-predictive cue (a green arc; 14.3% valid in their Experiment 1 and 50% valid in their Experiment 2), participants were presented with an array of one number (the target) and six letters (the distractors), equally spaced and arranged in a circle around centre. The contrast of the stimuli varied from 19% to 100%. The task was to first localize the target by indicating its location, and then identify the target by indicating what number it was. In both experiments, participants were more accurate, and to the same degree, for localizing the target and identifying the target on validly cued trials compared to invalidly cued trials. There was no increase in the size of the cueing effects for either the magnitude of the accuracy difference or the slope of accuracy by contrast function. If signal enhancement and uncertainty reduction could explain these results you would expect increases in the size of the cueing effects, whereas none were observed. In the present experiments we propose that strictly perceptual theories of attention are insufficient because attention is not an independent perceptual mechanism, but is dependent on the systems deployed to complete a task.

We used an exogenous, spatial pre-cue to orient attention and sequential or simultaneous presentation of stimuli to manipulate memory. The spatial cues always appeared after an initial interval of fixation at the start of a trial in the first three experiments and the cues were 100% valid in Experiment 1, 80% valid in Experiment 2 and 50% valid in Experiment 3. In the final two experiments there were two types of sequential trials: one where the cue appeared before the onset of the first stimulus and one where the cue appeared before the onset of the second stimulus. The cues were 80% valid in Experiment 4 and 50% valid in Experiment 5. Consequently, we were able to evaluate whether there are differences in the attentional effects for non-predictive and predictive spatial cues, as well as whether these effects interact with a manipulation of memory. As cued trials were intermixed with an equal number of uncued trials, we could also evaluate memory effects using the sequential-simultaneous comparison employed by Liu and Becker (2013). The present study therefore serves several functions. First, it is a replication of Liu and Becker's recent work on memory consolidation. Second, it presents new results relevant for the mechanisms by which attentional cues affect perceptual judgements of a continuous response metric, orientation. Thirdly, since memory and attention are manipulated together in the same task, we can evaluate their interaction or independence.

2.2 General Method

The procedures that were the same across all experiments are described here. Any differences or additions to individual experiments are described in the method section for that particular experiment.

2.2.1 Participants

The sample size for all experiments was chosen based on previous research using a similar protocol (B. Anderson & Druker, 2013). All participants reported normal or corrected-to-normal visual acuity. The experiments were approved by the Office of Research Ethics at the University of Waterloo, and all participants signed informed consent prior to participation.

2.2.2 Stimuli, design and procedure

The experiments were programmed in Python using the PsychoPy library (Pierce, 2007). Stimuli were displayed on a 33 x 26.5 cm CRT monitor with a screen resolution of 1024 x

768 pixels and a refresh rate of 84 Hz. Participants were seated at a viewing distance of 60 cm. All stimuli were presented on a gray background with a luminance of 39.3 cd/m^2.

The stimuli and procedure were designed to be a close replication of the stimuli and procedure used by Liu and Becker (2013). The addition of a spatial pre-cue is new in the experiments reported here. The stimuli consisted of circular sinusoidal gratings (size: 1.5°; spatial frequency: 2 cycles/deg., contrast: 0.7), circular noise masks (size: 1.8°; 200 white, one pixel dots), and a spatial pre-cue of four black dots (size: 0.3°). During the practice trials participants heard a high pitch tone if they were within 10 degrees of the correct orientation and a low pitch tone if they were outside of that range. No auditory feedback was provided during the experimental trials.

Participants made orientation judgements from memory in three general trial types: set size one (practice trials only), sequential, and simultaneous. The trial structure and timing for each trial type is shown in Fig. 2.1. In the set size one condition a single grating was presented in one of four possible locations, the corners of an imaginary square (size: 3°eccentricity). In the sequential condition two gratings were presented one after the other in two different locations, and in the simultaneous condition the two gratings were presented at the same time. For all three trial types, the gratings were followed by noise masks appearing in the same locations as the gratings. Stimulus locations were selected randomly with the proviso that both stimuli must be at separate locations. Stimulus orientation was selected pseudo-randomly from one of 12 possible orientations (10°, 24°, 38°, 52°, 66°, 80°, 100°, 114°, 128°, 142°, 156°, 170°; with horizontal designated as 0°). Two gratings could not have the same orientation on the same trial.

In half of the experimental trials a spatial cue preceded the onset of the stimuli. In the simultaneous block type it appeared before the onset of both stimuli, and in the sequential block type it appeared either before the first stimulus or before the second stimulus depending on the experiment. There was no spatial cue in the other half of the experimental trials or in the practice trials. We chose not to use a neutral cue appearing either at fixation or in all locations as we were more interested in making comparisons between cue probabilities and wanted to also replicate the results of Liu and Becker necessitating uncued trials. The validity of the spatial pre-cue differed by experiment. Participants were not made aware of the validity of the spatial cue, nor were they alerted to the presence of the cue in the instructions provided. In all experiments there were two different types of invalidly cued trials. Either the cue could appear at one of the two positions where neither Gabor would subsequently appear, or it could appear at the location where the Gabor that would **not** be probed for recall would appear. Where relevant, these types of invalid trials are distinguished in the analysis.

For all trials a white, 1.5°square appeared at the end of each trial and indicated the location of the grating that the participant was to use for their response. In addition, a grating (size: 1.2°; orientation: vertical [90°]) appeared in the centre of the screen and was used for participant responses. Participants rotated the response grating to match the orientation of the probed stimulus using four keys. The left and right arrow keys continuously rotated the response grating 1°, and holding down the ctrl key while using the left and right arrow keys rotated the response grating exactly 1°on each key press. In all trials the probed location was selected randomly. Participants were instructed to keep their eyes on fixation and their fingers on the response keys throughout the experiment, and to respond as accurately as possible (responses were therefore unspeeded).

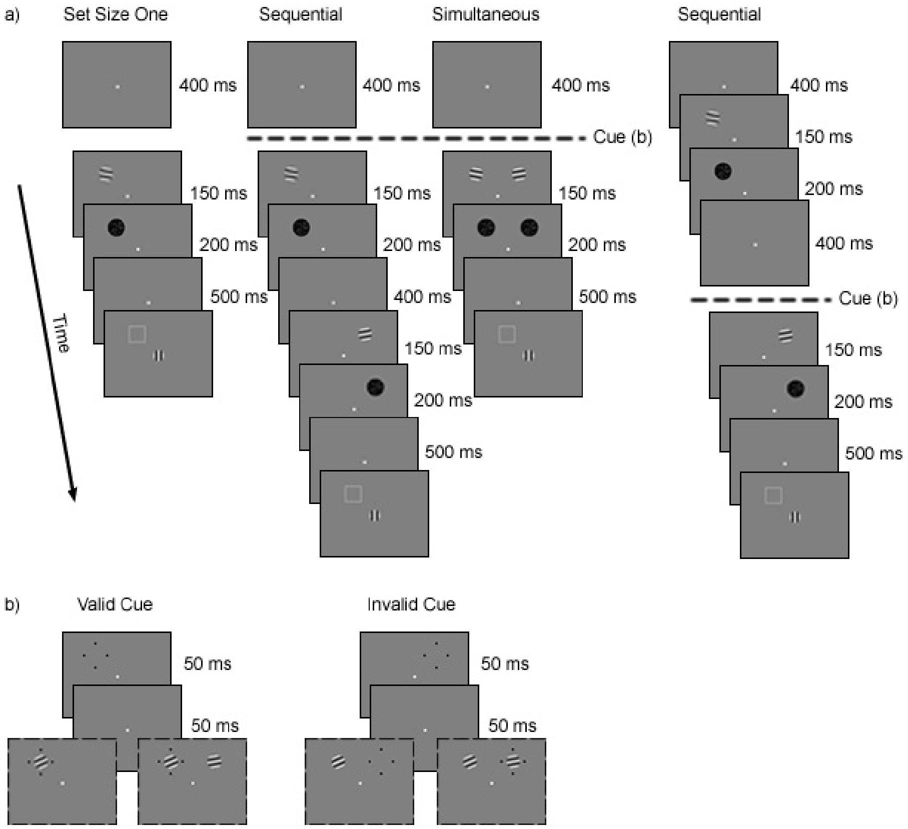


Figure 2.1: General procedure (Memory). a) The set size one condition only appeared in the practice trials, and for both the practice and the experiment the conditions were blocked. One or two circular gratings, which were backwards masked (black circles with white pixel dot noise), were displayed. In the sequential conditions the gratings were presented one after the other and in the simultaneous condition they were presented at the same time. When prompted for a response, a white square (response probe) appeared in a location previously occupied by a grating to indicate which grating should be recalled. Participants were required to rotate a central response grating to match the angle of the indicated grating. b) On half of the experimental trials a spatial pre-cue, consisting of four black dots, appeared before the presentation of the first stimulus in one sequential block type (all experiments) and before the second stimulus in another sequential block type (Experiment 4 and Experiment 5). In the simultaneous condition it appeared before the presentation of both stimuli. The stimuli and the cue disappeared together in all cases. A valid trial was one in which the cue and the response probe appeared in the same location, and an invalid trial was one in which the cue and the response probe appeared in different locations.

2.2.3 Data analysis

All analyses were conducted in R using the *heplots* (Fox, Friendly, & Monette, 2014), *nlme* (Pinheiro, Bates, DebRoy, Sarkar, & Team, 2014), and *multcomp* (Hothorn, Bretz, & Westfall, 2008) packages. The *ggplot2* package was used to create all plots (Wickham, 2009).

Many of the figures presented are box plots, a standard data visualization. The lower and upper bounds of the 'box' are the first and third quartile of the data. The difference between these values is called the interquartile range (IQR). Outliers are defined as any point that is three or more times the IQR above the third quartile or below the first quartile and are the points on the box plot. If there are no outliers, the 'error bars' are the maximum and minimum thresholds of the data. If there are outliers, the 'error bar' on the side or sides with outliers is instead 1.5 times the interquartile range.

The error between true orientation and judged orientation on each trial was calculated by subtracting the true orientation from the judged orientation and wrapping it to an interval between -90°and +90°. No effects of bias were found for any condition in any experiment so the analysis of bias is not reported here.

2.3 Experiment 1

The purpose of the first experiment was two-fold: would we replicate the results of Liu and Becker (2013) when a cue was introduced on some trials, and would there be evidence of an interaction between cue effects and memory effects. A 100% valid spatial cue was used to maximize the potency of the cue.

2.3.1 Method

Participants

Thirty-four students participated in exchange for credit applied to a University of Waterloo undergraduate psychology course.

Stimuli, design and procedure

The validity of the pre-cue was 100%. The practice trials consisted of 15 trials of each trial type, blocked, and with no spatial cue for a total of 45 practice trials. Following the practice trials, participants were presented with two superblocks each consisting of one 75 trial sequential block, and one 75 trial simultaneous block in random order for a total of

300 experimental trials. Participants were informed of the block type at the beginning of each block, and the experiment took approximately thirty minutes.

2.3.2 Results and Discussion

One of the main results of Liu and Becker (2013) was a reduced error variance for orientation judgements on sequential trials. As a replication, we performed this analysis on our uncued trials (the trials that were identical to those of Liu and Becker (2013)). Fig. 2.2 illustrates our replication [$F(1,33) = 13.76$, p <.001, $\eta_p^2 = .29$]. Orientation judgements on sequential trials were less variable. The magnitude of the variance we found was very similar numerically to that reported by Liu and Becker (2013).

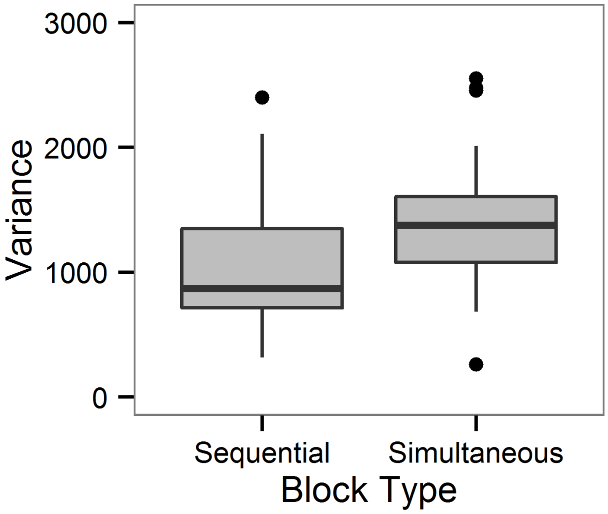


Figure 2.2: When trials were uncued, error variance was lower on sequential than simultaneous trials in Experiment 1.

Next, we directly compared response precision across block types with and without cueing. Our metric for quantifying precision was the median absolute deviation. This measure is preferable to the variance (or standard deviation) when data are not normally distributed (Gorard, 2005). It is less sensitive to outliers than is the variance (which measures the squared deviation), and has been used in prior work of this type (B. Anderson & Druker, 2013; Prinzmetal, Amiri, Allen, & Edwards, 1998; Prinzmetal, Nwachuku, Bodanski, Blumenfeld, & Shimizu, 1997). The main effect of cueing on the median, absolute error was not significant [$F(1{,}33) = 0.444$, $p = .51$]; however, consistent with a difference between the effects of memory and attention on response variability there was an interaction between block type and cueing [Fig. 2.3; $F(1{,}33) = 5.131$, $p < .05$, $\eta_p^2 = .13$]. Post-hoc analyses indicated that there was a trend of cueing reducing the median, absolute error only on simultaneous trials [Simul.: $F(1{,}33) = 3.472$, $p = .07$, $\eta_p^2 = .10$; Seq.: $F(1{,}33) = 1.095$, $p = .30$].

Because we used a 100% valid cue, we cannot evaluate from these data whether the principal effect of a cue may be to worsen performance when it is invalid. This might explain the failure to find a main effect for cueing. Furthermore, the nature of the sequential trials makes interpreting the absence of a cueing effect challenging. Firstly, there are differences in stimulus onset asynchrony (SOA) when the target is the first stimulus and when it is the second stimulus. Previous work has demonstrated that the magnitude and direction

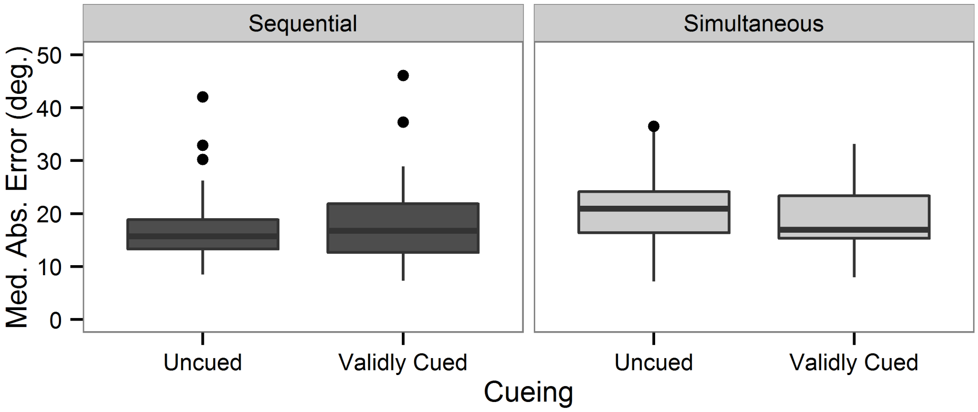


Figure 2.3: Cueing reduced the median, absolute error only on simultaneous trials in Experiment 1.

of cueing effects is dependent on SOA (Posner, 1980). Secondly, it is possible that there is a floor effect because of the reduced variability on sequential trials.

In summary, we have shown that variability was lower on sequential than simultaneous trials, and that a 100% valid spatial pre-cue may reduce errors on cued trials on simultaneous trials only. Consequently, we have preliminary evidence that memory and attention affect orientation judgements via different routes, and that attention may facilitate performance only when memory consolidation demands are high. In the next experiment we address the concern that the size of our cueing effect may be due to the absence of invalid trials.

2.4 Experiment 2

In order to address the possibility that the effects of cueing are largely attributable to invalid cueing and to investigate the effects of cueing on sequential trials free from floor effects, Experiment 2 repeats the procedures of Experiment 1, but with an 80% valid cue.

2.4.1 Method

Participants

Thirty-five students participated in exchange for credit applied to a University of Waterloo undergraduate psychology course.

Stimuli, design and procedure

The only difference between Experiment 1 and Experiment 2 was that the validity of the pre-cue was 80% in Experiment 2.

2.4.2 Results and Discussion

Two participants were removed because a technical snafu resulted in the absence of invalid trials, and one participant was removed for responses indistinguishable from chance.

To evaluate consistency across experiments, we compared the variance of responses on uncued trials. We found results almost identical to those of Experiment 1. Variability of responses on uncued trials was lower for sequentially presented stimuli [Fig. 2.4; $F(1,33) = 41.11$, p <.001, $\eta_p^2 = .57$].

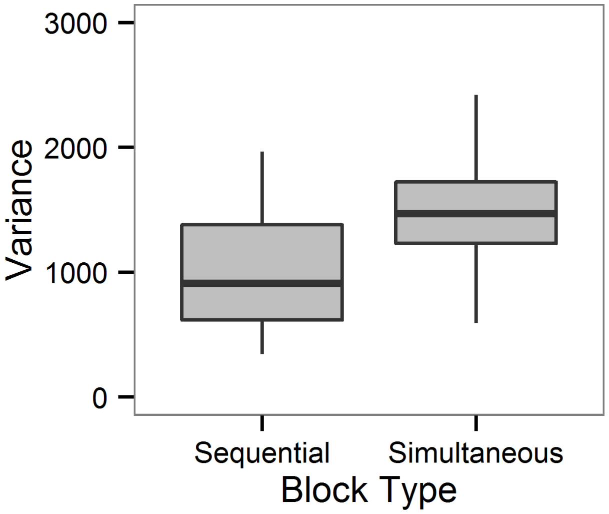


Figure 2.4: Error variance was lower on sequential trials in Experiment 2.

The main effect of cueing on the median, absolute error was significant [$F(2,62) = 35.57$, p <.001, $\eta_p^2 = .53$], as was the interaction between block type and cueing [Fig. 6a; $F(2,62) = 9.787$, p <.001, $\eta_p^2 = .24$]. Visual inspection of Fig. 2.5a shows that performance on sequential trials was generally better and, as in Experiment 1, there was little difference between uncued and validly cued trials. In contrast, on simultaneous trials, validly cued trials reduced the magnitude of errors in addition to invalidly cued trials increasing it. The post-hoc Tukey contrasts for the differences between the levels of cueing on sequential and simultaneous trials are provided in Table 4.1.

Contrast	**Sequential** Est. (z-value)	**Simultaneous** Est. (z-value)
Uncued - Invalid	-3.878 (-2.78*)	-9.88 (-5.23***)
Valid - Invalid	-3.53 (-2.53*)	-14.42 (-7.63***)
Valid - Uncued	0.35 (0.25)	-4.54 (-2.40*)

*p<.05, **p<.01,***p<.001

Table 2.1: Linear Tukey contrasts on precision between the levels of cueing on sequential and simultaneous trials in Experiment 2 (Memory).

It is possible the absence of an effect of valid cueing on sequential trials may be explained by a floor effect; however, similar orientation judgement experiments (e.g. B. Anderson & Druker, 2013) have shown better performance with lower contrasts. Further, the standard deviations in the Liu and Becker (2013) study, which we replicate, are smaller (see below). Thus a floor effect seems unlikely to account for these data.

In summary, Experiment 2 confirmed that the effects of predictive spatial pre-cues on orientation judgements are modulated by the demand on memory consolidation. When presented sequentially the consolidation of both stimuli can take place. Then spatial cues do not improve performance, but they can worsen it. When demands are higher, because two stimuli must be consolidated simultaneously, spatial cues aid performance on valid trials and reduce it on invalid trials.

2.5 Experiment 3

So far we have demonstrated that predictive valid cues improve performance by reducing error magnitude on simultaneous trials, and that invalid cues reduce performance on both simultaneous and sequential trials. Predictive spatial cues engage a mixture of endogenous and exogenous attention, and so, not surprisingly, their effects are different than the strictly exogenous case of non-predictive cues (Enns & Brodeur, 1989; Eriksen & Yeh, 1985; Johnson & Yantis, 1995; Jonides, 1980). In Experiment 3, we used a 50% non-predictive spatial cue to isolate the effects of exogenous attention. Comparing Experiment 2 (80% valid cues) with Experiment 3 (50% valid cues) will permit us to assess how much endogenous mechanisms are contributing to the performance effects.

2.5.1 Method

Participants

Thirty-five students participated in exchange for credit applied to a University of Waterloo undergraduate psychology course.

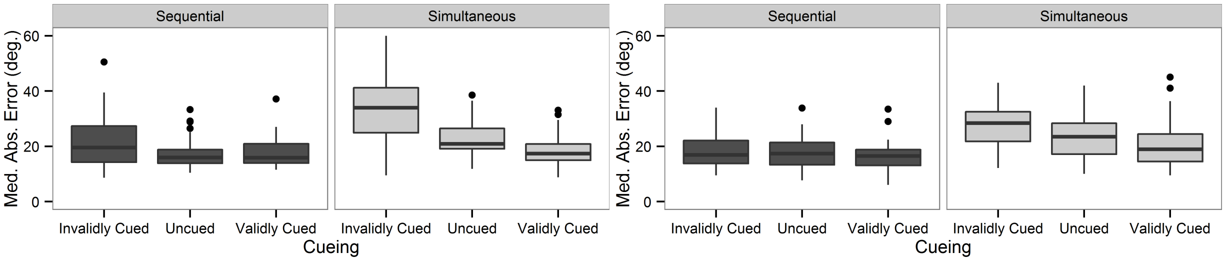
Stimuli, design and procedure

The only difference between Experiment 2 and Experiment 3 was that the validity of the pre-cue was 50% in Experiment 3.

2.5.2 Results and Discussion

Three participants were removed for performance indistinguishable from chance. As in Experiment 2, the main effect of cueing [$F(2{,}60) = 16.01$, p <.001, $\eta_p^2 = .35$] and the effect of the interaction between block type and cueing [Fig. 2.5b; $F(2{,}60) = 3.925$, p <.05, $\eta_p^2 = .12$] were significant and appear similar.

Experiment 3 demonstrated that the different effects of the cue between low and high memory consolidation demands are not dependent on the cue being predictive. Valid cueing did not improve performance on sequential trials whereas it did on simultaneous trials, regardless of whether the cue provided any spatial information about target position. In all cases, and regardless of memory demands, invalid cues worsen performance.



(a) Experiment 2

(b) Experiment 3

Figure 2.5: Only invalid cues affected performance on sequential trials, whereas performance was affected by both invalid and valid cues on simultaneous trials.

2.6 Experiment 4

The first three experiments taken together suggest that, when used in difficult tasks with multiple stimuli, attentional cues improve performance only when the demand on memory consolidation is high. We have also shown that predictive and non-predictive cues alike can help prioritize stimuli for processing, and that spatial cues cannot be ignored, even when they don't seem to give us any valid information about target locations.

Direct comparisons between sequential and simultaneous trials in these first three experiments is complicated however by the fact that the cue always appeared before the onset of the first stimulus, regardless of whether the participant was to respond to the first or second stimulus in a sequential trial. This experimental structure keeps the overall timing of sequential and simultaneous trials the same, but at the expense of inducing different cue target timings for sequential trials when the target is the first or second stimulus presented. An alternative approach is to present the cues sometimes before the first stimulus of a sequential trial, and sometimes before the second. This would keep cue target timings the same. This is what was done for the next two experiments where we repeat the manipulations of predictive (80% valid; Experiment 4) and non-predictive (50% valid; Experiment 5) cueing.

2.6.1 Method

Participants

Thirty-four students participated in exchange for credit applied to a University of Waterloo undergraduate psychology course.

Stimuli, design and procedure

In Experiment 4 there were two sequential block types. In one type the cue appeared before the onset of the first stimulus and in the other the cue appeared before the onset of the second stimulus. Simultaneous trials were unchanged. The spatial pre-cue was 80% valid. Following the practice trials, participants were presented with two superblocks each consisting of one 100 trial sequential block with the cue appearing before the first stimulus, one 100 trial sequential block with the cue appearing before the second stimulus, and one 100 trial simultaneous block in random order for a total of 600 experimental trials. Participants were informed of the block type (without information about the cue for sequential trials) at the beginning of each block, and the experiment took approximately one hour.

2.6.2 Results and Discussion

One participant was removed for performance indistinguishable from chance. To assess the effect of cueing for targets appearing in the first or second position without different cue target timings we began by analyzing only those trials where the cue and target appeared in the same temporal epoch. That is, if the stimulus that we would eventually ask the participant to report on was to be the first one shown, we only include trials when the cue appeared before the first stimulus, and if the stimulus to be reported was to be the second one shown we only include those trials when the cue appeared before the second stimulus. This gives a consistent timing for validly cued trials. It also yields two types of invalid trials. Either we cue the location of empty space, that is a location where no stimulus is shown on that trial, or invalidly cue the wrong stimulus, that is the cue appears at the same spatial position as the stimulus the participant will not be asked to judge.

When evaluating the effects of cueing, we again find a main effect of cueing [$F(2,64)$

= 38.1, p <.001, $\eta_p^2 = .54$] and a block type - cueing interaction [Fig. 7a; $F(4,128) = 7.723$, p <.001, $\eta_p^2 = .19$] on the median, absolute error.

Visual inspection of Fig. 2.6 demonstrates that the pattern of results seen in Experiment 4 largely replicate the results of Experiment 2 (Fig. 2.5a), namely that a predictive spatial pre-cue improved performance on valid trials and hurt performance on both invalidly cued simultaneous trials and sequential trials. Furthermore, it appears that performance on valid trials is the same across trial types implying that spatial attention selects information for processing when multiple stimuli have to be consolidated at the same time by giving priority to the attended stimulus. This assertion is supported by the post-hoc Tukey contrasts provided in Table 2.2. When the spatial information is absent or wrong, performance is hurt. When the demand on memory consolidation is high, as when the stimuli appear on the screen together for a brief duration, attention must be re-oriented between the two potential target stimuli.

Contrast	**Invalid**	**Uncued**	**Valid**
	Est. (z-value)	Est. (z-value)	Est. (z-value)
Seq2 - Seq1	-3.96 (-2.24)	-5.67 (-4.80***)	-4.40 (-5.10***)
Simul. - Seq1	4.73 (2.67*)	0.16 (0.14)	-3.51 (-4.10***)
Simul. - Seq2	8.69 (4.91***)	5.84 (4.94***)	0.88 (1.02)

*p<.05, **p<.01,***p<.001

Table 2.2: Linear Tukey contrasts on precision between block types (Seq1: sequential trials with the cue appearing before the first stimulus; Seq2: sequential trials with the cue appearing before the second stimulusl Simul: simultaneous trials) on invalid, uncued and valid trials in Experiment 4 (Memory)

Up to this point we have demonstrated consistent differences of the effects of a spatial pre-cue between the level of the demand on memory consolidation, that these differences are not dependent on cue validity, and that invalid trials make performance worse across the board. This avoids the question of whether the type of invalid trial is relevant and whether that depends on the temporal position of the spatial pre-cue. Two types of invalid trials were possible: an invalid trial could be one where the cue appeared in a location where neither stimulus appeared (empty space) or it could be one where the stimulus that was not the target was cued. We evaluated whether there were differences in the effect of an invalid cue on the median, absolute errors and found that there was none (Fig. 2.7a). Indeed, the main effect of invalid cue type on the median, absolute error of orientation judgements was not significant [$F(1,32) = 1.831$, $p = .19$], and neither was the interaction with block type [F(1,32) = 1.103, $p = .30$].

2.7 Experiment 5

In Experiment 4 we demonstrated that the temporal position of the cue was irrelevant for predictive cues and that the results largely replicated the results of Experiment 2. In this final experiment, we turn to non-predictive cues.

2.7.1 Method

Participants

Thirty-five students participated in exchange for credit applied to a University of Waterloo undergraduate psychology course.

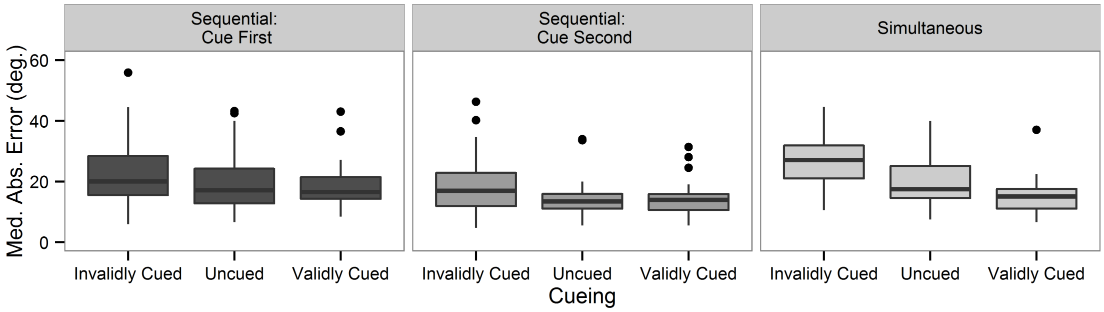
Stimuli, design and procedure

The only difference between Experiment 4 and Experiment 5 was the validity of the spatial pre-cue. The cue was 50% valid.

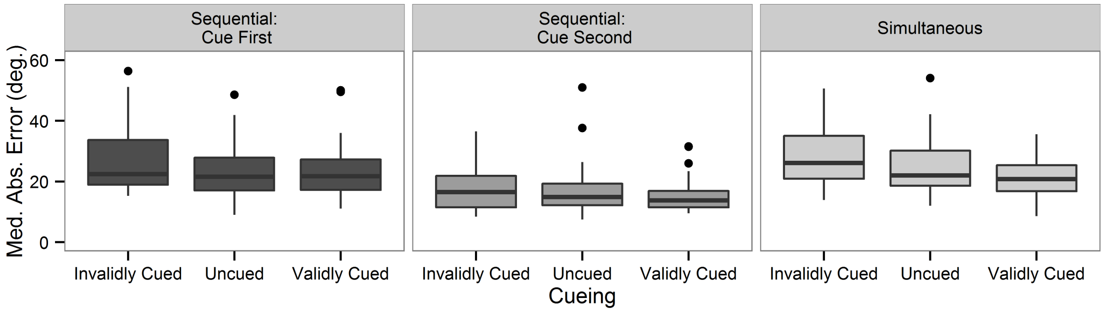
2.7.2 Results and Discussion

One participant was removed for performance indistinguishable from chance. To keep the timing consistent for validly cued trials, only the trials on which the cue and the target appeared in the same temporal epoch were included in this analysis.

The main effect of cueing on the median, absolute error [$F(2{,}66) = 18.73$, $p < .001$, $\eta_p^2 = .36$], as well as the interaction between cueing and block type were significant [Fig. 2.6b; $F(4{,}132) = 3.633$, $p < .01$, $\eta_p^2 = .10$]. The results replicate those of the prior experiments, namely, that the difference in the effect of the cue between sequential and simultaneous block types was not dependant on the predictive value of the cue, that invalid trials hurt performance universally, and that valid trials help performance only when the demand on memory consolidation was high.



(a) Experiment 4



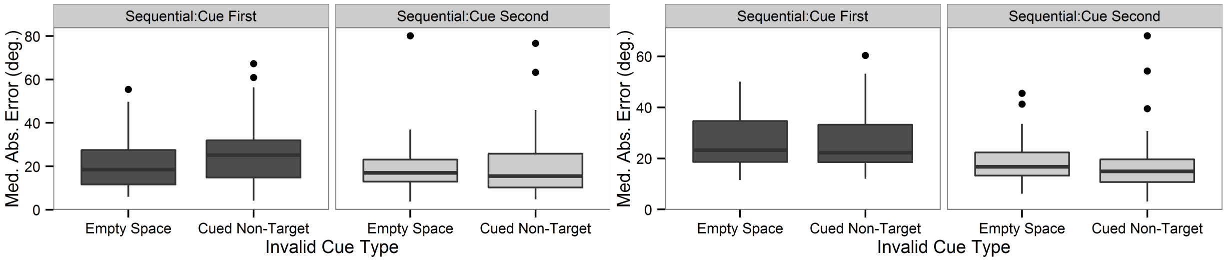
(b) Experiment 5

Figure 2.6: The results of Experiment 4 (a) largely replicate the results of Experiment 2 (Fig. 2.5a, Page 36), namely that the predictive spatial pre-cue affected performance for simultaneous trials, but not as much so for sequential trials. This result is the same for Experiment 5 (b) and Experiment 3 (Fig. 2.5b, Page 36).

Finally, we evaluated whether the type of invalid cue mattered and replicated the result of Experiment 4 that there was no difference in performance between when the invalid cue cued empty space and when the non-target stimulus was cued [$F(1{,}33) = 0.39$,

p = .54]; there was as well no interaction with block type [Fig. 2.7b; $F(1,33) = 0.285$, $p = .60$].

The results across the five experiments have been quite consistent, and so as one final demonstration we collapsed the data across all experiments and found that the main effect of cueing [$F(2,68) = 10.561$, $p < .01$] and the interaction between block type and cueing [Fig. 2.8; $F(2,68) = 6.536$, $p < .01$] were significant. *The result is consistent with the results of all five experiments: spatial pre-cues reduce performance universally on invalid trials, but only improve performance on valid trials when the demand on memory consolidation is high.*



(a) Experiment 4

(b) Experiment 5

Figure 2.7: Performance was the same in Experiment 4 (a) and Experiment 5 (b) when the invalid cue appeared in the location of the non-target stimulus and when it appeared in empty space.

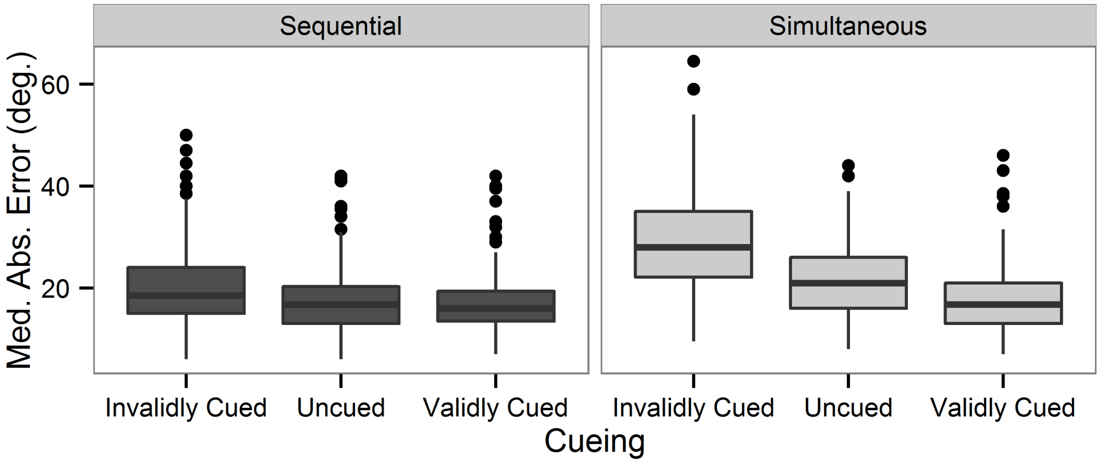


Figure 2.8: Data from all five experiments amalgamated together.

2.8 Mixture Model Analysis (Experiments 1, 2 & 3)

In order to evaluate more specifically the mechanisms behind the memory consolidation effect, operationalized by presenting the stimuli sequentially or simultaneously, Liu and Becker (2013) reported a mixture model analysis. They fit their error data to a mixture that included a uniform component (to capture guessing), and a von Mises function to capture response standard deviation. The mixture model had three free parameters: the mean of the von Mises, the width of the von Mises, and the mixture proportion. Changes in the first term as a function of block type would indicate differences in response bias, the width term would reflect differences in response standard deviation, and the mixture coefficient, the probability of guessing. The standard deviation parameter is descriptively referred to as a model-based precision by Liu and Becker (2013); however, to avoid confusion between the model-free precision results and the model-based precision results reported here, we refer to the latter as the standard deviation of the model fit.

Liu and Becker (2013) reported that the only parameter to change between the sequential and simultaneous trials was the guessing component, and they concluded that memory consolidation has its principal effect on error variability by reducing the probability of guessing and not by affecting the judgement standard deviation per se. We repeated the procedure used by Liu and Becker (2013) as another test of the replicability of their results, but we also included the cued trials to elaborate on the dependence of memory and attention observed in the prior analysis of precision. We excluded Experiment 4 and Experiment 5 from this analysis as the results of the mixture model fits were redundant with Experiments 2 & 3 as the mixture model parameters for Experiment 4 were concordant with Experiment 2 and the mixture model parameters for Experiment 5 were concordant with Experiment 3.

There is considerable discussion on the right way to model memory (Ma, Husain, & Bays, 2014; van den Berg, Awh, & Ma, 2014; van den Berg, Shin, Chou, George, & Ma, 2012). Particularly contentious is the debate on whether the mixture model employed by Liu and Becker (2013) is a good way to model such data. The parameters can be difficult to interpret as they depend on the validity of the model. It is sometimes the case that the residuals of the mixture model are structured and this poses a challenge to interpreting the meaning of any differences in model parameters. It is therefore important to emphasize that we do not wish to draw conclusions about the structure of memory or the underlying processes. Rather, we have employed it as a descriptive tool to elaborate on the behavioural results reported above.

We fit a mixture model of the above type to individual participant data using a custom script written in R. We evaluated standard deviation and guessing parameters with 2 (Block Type: Sequential vs. Simultaneous) x 3 (2 in Experiment 1) (Cueing: Invalid vs. Uncued vs. Valid) ANOVAs. We calculated the residuals and found them to be small (less than 0.0015) so we have not reported them here.

With respect to memory consolidation, we replicated Liu and Becker (2013). In Experiment 1 and Experiment 2, participants made more guesses on simultaneous trials than sequential trials [E1: $F(1{,}33) = 20.92$, p <.001, $\eta_p^2 = .39$; E2: $F(1{,}31) = 11.08$, p <.01, $\eta_p^2 = .26$] and standard deviation did not significantly differ between block types [E1: $F(1{,}33) = 0.377$, $p = .54$; E2: F(1,31) = 3.459, $p = .07$]. In Experiment 3 the guessing parameter was not significantly affected [F(1,30) = 0.747, $p = .39$], but the standard deviation parameter was [$F(1{,}30) = 16.33$, p <.001, $\eta_p^2 = .35$]. It is possible that the interaction between the non-predictive spatial cue and the consolidation condition affected the overall distribution of errors differently when the cue was non-predictive compared to when it was predictive.

With respect to cueing, the main effect of cueing on guessing was not significant when the cues were predictive [E1: $F(1{,}33) = 0.898$, $p = .35$; E2: $F(2{,}62) = 0.739$, $p = .48$], but it was significant when the cues were non-predictive [E3: $F(2{,}60) = 5.749$, p <.01, $\eta_p^2 = .16$]. The post-hoc linear Tukey contrasts indicated that only the difference between invalid and valid trials was significant [estimate = .13, z = 3.263, p <.01]. There was no main effect of cueing on the standard deviation in any experiment [E1: $F(1{,}33) = 4.119$, $p = .05$; E2: $F(2{,}62) = 2.849$, $p = .07$; E3: $F(2{,}60) = 0.322$, $p = .73$].

There was a trend, however, for cueing to affect standard deviation when the cues were predictive and it may not have reached significance because of undetectably small differences on sequential trials. Indeed, the interaction between block type and cueing on standard deviation (Fig. 2.9a and Fig. 2.10a) was significant when the cues were predictive [E1: $F(1{,}33) = 7.81$, p <.01, $\eta_p^2 = .19$; E2: $F(2{,}62) = 6.628$, p <.01, $\eta_p^2 = .18$] and not when they were non-predictive [E3: $F(2{,}60) = 1.692$, $p = .19$]. When the cues were predictive, the main effect of cueing on standard deviation was not significant on sequential trials [E1: $F(1{,}33) = 0.138$, $p = .71$; E2: $F(2{,}62) = 1.235$, $p = .30$], but it was significant on simultaneous trials [E1: $F(1{,}33) = 11.72$, p <.01, $\eta_p^2 = .26$; E2: $F(2{,}62) = 5.771$, p <.01, $\eta_p^2 = .16$]. The standard deviation was lower on cued trials compared to uncued trials in Experiment 1, and lower on valid trials compared to invalid trials in Experiment 2 (Table

2.3).

Contrast	**Estimate** (deg.)	**Z-value**	**P-value**
Valid - Uncued	-7.44	-1.54	.27
Invalid - Uncued	9.18	1.86	.15
Invalid - Valid	16.04	3.39	<.01

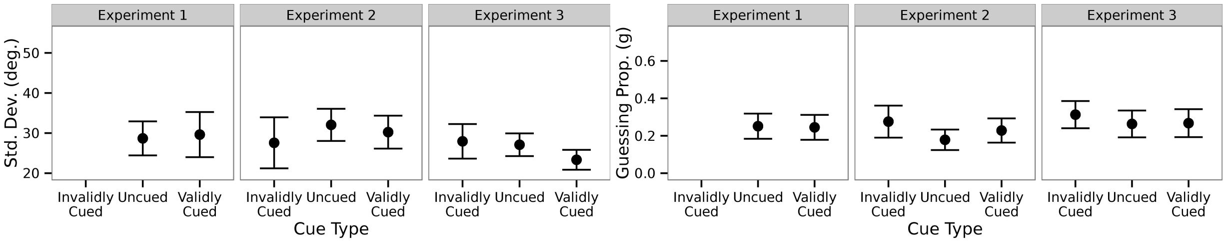
Table 2.3: Linear Tukey contrasts of the mixture model standard deviation between the levels of cueing on simultaneous trials in Experiment 2 (Memory).

With respect to guessing, the interaction between block type and cueing (Fig. 2.9b and 2.10b) was not significant when the cues were predictive [E1: $F(1{,}33) = 1.88$, $p = .18$; E2: $F(2{,}62) = 1.069$, $p = .35$], but it was significant when the cues were non-predictive [$F(2{,}60) = 5.815$, p <.01, $\eta_p^2 = .16$]. When the cues were non-predictive, the main effect of cueing on guessing was not significant for sequential trials [$F(2{,}60) = 1.926$, $p = .16$], but it was significant for simultaneous trials [$F(2{,}60) = 6.549$, p <.01, η_p^2 =.18]. Participants made fewer guesses when the cue was valid compared to uncued and invalid trials (Table 2.4).

Contrast	**Estimate** (deg.)	**Z-value**	**P-value**
Valid - Uncued	-9.17	-2.51	<.05
Invalid - Uncued	3.44	1.00	.58
Invalid - Valid	12.61	3.51	<.01

Table 2.4: Linear Tukey contrasts of the mixture model guessing proportion between the levels of cueing on simultaneous trials in Experiment 3 (Memory).

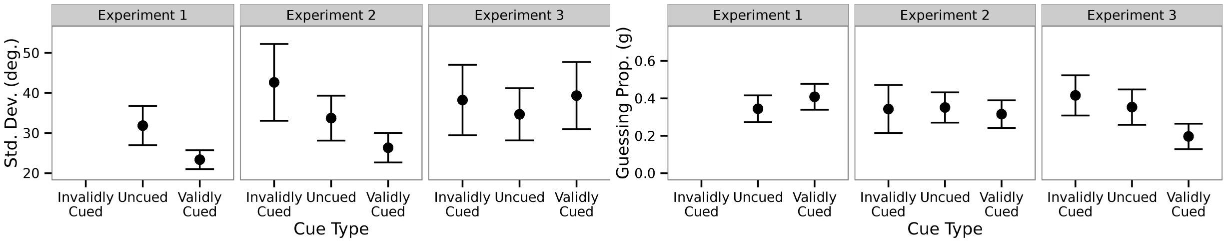
In summary, the mixture model results indicate that the mechanism of the effects on precision depend on whether the cues are predictive or non-predictive. For predictive cues, precision was affected because errors were overall more (valid) or less (invalid) concentrated at the centre of the distribution. For non-predictive cues, guessing was affected because the likelihood the target would be consolidated was improved, which reduced guessing on valid trials and increased guessing on invalid trials.



(a) Standard Deviation

(b) Guessing

Figure 2.9: Mixture model fit results on sequential trials for standard deviation (a) and guessing (b).



(a) Standard Deviation

(b) Guessing

Figure 2.10: Mixture model fit results on simultaneous trials for standard deviation (a) and guessing (b).

2.9 Discussion

The effect of memory and attention on perceptual judgements for orientation seem to interact. We replicated the memory effects reported by Liu and Becker (2013), namely that variance was lower on sequential trials than simultaneous trials, and that the mixed model fitting showed the salient difference to be guessing proportion.

With respect to attention, the effects are more complex. In cases where spatial cues are 100% predictive it is not possible to compare validly and invalidly cued trials, but the fact that valid cueing facilitated performance on simultaneous trials and did not facilitate it on sequential trials suggests that valid cueing only benefits performance when it can prioritize stimuli for consolidation. Indeed, work by Yeh, Yang, and Chiu (2005) supports this claim. In their experiments participants were required to detect either changes in features or changes in conjunctions of features. Attentional shifts were manipulated during the retention interval. Central and peripheral letter cues had similar impacts on the detection of feature and conjunction changes suggesting that the cues prioritized the selection of information for consolidation rather than improving the binding of features. One possibility is that these attentional effects occurred at the level of perception via improvements in perceptual representations; however, this explanation fails to account for the effects of post-cues on response precision discussed in the introduction to this chapter. Further, Yeh et al. (2005) also demonstrated that post-cues improved detection only at short delays during which consolidation occurred supporting the hypothesis that attentional effects occurred at the level of memory.

This result appears to contradict prior work demonstrating increased precision on valid trials in the case of a single stimulus (B. Anderson & Druker, 2013). Both multiple sequential stimuli and single stimulus orientation judgement experiments involve consolidating one target at a time, and yet we did not find the valid cueing effects typically found with single stimuli experiments on sequential trials. The fact that precision was reduced on invalid trials rules out the possibility that participants were ignoring the cues. Furthermore, excluding the effect of SOA in Experiment 4 and Experiment 5 still did not produce valid cueing effects on sequential trials, and there was no difference between the effects of a predictive and non-predictive cue suggesting that the effect of the cue was not mediated by top down processes. Our results therefore suggest that attention and memory consolidation are not separable and independent effects in cases where multiple things have to be remembered. Rather, they are dependent and interacting and this effect does not appear to be influenced by top down processes.

The aggregate effects on precision were independent of cue validity, but the mixture model parameters revealed differential effects. When the cues were predictive, differences in performance were explained by differences in the standard deviation of the error distributions. In contrast, when the cues were non-predictive, differences in precision were explained by differences in guessing. A changing mechanics of cue effects with cue validity is consistent with the large amount of data showing that we implicitly monitor our environment for statistical regularity (Fiser & Aslin, 2001; S., 2006; Saffran, Aslin, & Newport, 1996; N. Turk-Browne, Scholl, Chun, & Johnson, 2009; N. B. Turk-Browne, 2012).

Also noteworthy is the fact that precision on valid trials was the same for sequential and simultaneous trials, whereas precision on invalid trials was much worse on simultaneous trials compared to sequential trials. Most of the effect of the cue was therefore in making performance worse on invalid trials. This might be explained by the fact that attentional effects are at least in part mediated by the inhibition of distractors (Shiu & Pashler, 1994). In cases where multiple stimuli must be consolidated at the same time and attention is validly oriented, the non-target stimuli is suppressed and consolidation occurs as it would in the case of a single stimulus. As a result, performance is much worse on invalid trials because stimuli in uncued locations are suppressed as presumed distractors.

In summary, we have provided evidence from a single experimental task and using a common analytic procedure that memory and attention have interacting effects on perceptual judgements; performance was facilitated by a valid cue only on trials where the display consisted of multiple stimuli. When the display consisted of a single stimulus, valid cueing had no effect on precision, but invalid trials reduced precision. Further, we demonstrated that the precision effects of spatial attention on memory consolidation were not dependent on cue predictability; however, the mechanism by which spatial attention affects precision may be dependent on how we implicitly monitor our environment for statistical regularities.

Chapter 3

Performance-based reward distributions and spatial attention effects may be dependent

3.1 Introduction

The results of the experiments presented in Chapter 2 demonstrated that attention and memory interact and are synergistic, and that there are differences between predictive and non-predictive spatial cues and how they affect the shape of an error distribution, as evaluated by the model parameters. One explanation for this difference is that predictive cues communicate importance about a spatial location by indicating a target's location with an accuracy greater than chance whereas non-predictive cues provide no information either way about spatial locations. Reward is another mechanism that communicates importance (e.g., Della Libera & Chelazzi, 2009; Kiss, Driver, & Eimer, 2009; Krebs, Boehler, & Woldorff, 2010; Lee & Shomstein, 2014; Muhle-Karbe & Krebs, 2012; Raymond & OBrien, 2009; Rutherford, OBrien, & Raymond, 2010; Serences, 2008), and this is one motivation for the three experiments presented in the present chapter. As with memory and attention, reward effects on visual perception parallel the effects of attention on visual perception. Effects in reward experiments are commonly described as effects on attention in the absence of explicit manipulations of attention, consequently another goal of the present experiments was to evaluate their effects when manipulated together.

As organisms that rely heavily on visual information, we have developed systems for rapidly prioritizing the visual information we are constantly bombarded with. Early humans would have relied on such systems to evaluate quickly, for instance, whether what they just saw out of the corner of their eye was predator or prey. Developing systems for assigning importance to some clues (stimuli) over others would have been be essential to survival. Through experience and observation some clues would become associated with positive outcomes (that wasn't anything that could eat me) while others would become associated with negative outcomes (that was a tiger and it just ate my brother). Developing systems for making these decisions rapidly and effortlessly would then be essential, and indeed prior work as demonstrated such systems exist. For instance, we know that rewarded stimuli or features become salient, which causes a reduction in response times to them (Hickey et al., 2010a). We also know that a bias towards a target location can develop when target selection resulted in reward (B. A. Anderson et al., 2011; Hickey et al., 2010b).

Reward experiments typically involve associating features or objects with monetary rewards and observing differences in responses to them when either some are rewarded and some are not, or when some are highly rewarded and some are rewarded to a lesser extent. Reward experiments then typically involve fixed, discrete rewards. In one such experiment. Anderson, Laurent and Yantis (2011) trained participants on a stimulus (red or green circle with an angled line segment in the interior) and associated the colours with a probability of a large reward. For one colour, correct responses were awarded with five cents 80% of the time and one cent 20% of the time and for the other colour this was reversed. As such, colour became associated with either a high or low chance of the larger reward (five cents). The authors observed that response times to identify the target in a different task where the target was identified by a unique shape were slower when a distractor was coloured with the colour associated with a high chance of reward from the training set.

Similarly, Failing and Theeuwes (2014) demonstrated that non-salient cues that are associated with reward capture attention similar to the attentional capture of salient spatial cues. The experiment consisted of two phases: a training phase and a testing phase. During the training phase participants searched for a target letter that was always located inside a coloured circle. One coloured circle was always associated with a reward and another coloured circle was not associated with reward. The testing phase involved a Posner spatial cueing task where the spatial cues were the coloured circles. Response times to targets appearing inside previously rewarded, coloured circles were faster than targets appearing inside previously unrewarded, coloured circles. Further, responses to targets appearing inside an untrained, coloured circle were slower than both. These results demonstrated that spatial cues associated with rewards affect response times similar to typical exogenous spatial cues that appear abruptly and briefly on the display.

These experiments all involve discrete rewards. Less understood is how reward affects responses when the rewards are graded and associated with performance. Further, prior experiments have typically focused on response times without assessing accuracy, if only because their methods did not afford the opportunity. Orientation judgement tasks allow both for making reward effects graded and for more granular investigations of the effects of manipulations on accuracy.

We observed in Chapter 2 that the probability associated with a spatial cue affects the shape of the error distribution. We know from prior work that rewarded objects serving as spatial cues have effects similar to abrupt-onset, exogenous spatial cues. The present experiments combined these two observations to ask whether rewards that are differentially associated with the distribution of errors have differential effects on the shape of error distributions. This was the primary motivation for using rewards that were graded.

In Chapter 2, we evaluated differences in the shapes of the error distributions using a mixture model. The proper form for memory models is the subject of contentious debate in the memory literature. As we did receive criticism for our use of the mixture model we opted to evaluate the shape of the distribution using a single statistic, kurtosis, instead of fitting a mixture model. Kurtosis is the fourth moment of a distribution (where mean is the first, variance is the second, and skewness is the third). It is a measure of tails and peakedness of a distribution where positive numbers indicate heavy tails and high peakedness and negative numbers indicated lighter tails and flatness (DeCarlo, 1997). Kurtosis is typically evaluated as excess kurtosis, kurotsis greater than the kurtosis of a normal distribution. Normal distributions have an excess kurtosis of zero (Fig. 3.1; mesokurtic). Distributions which are more peaked and have heavier tails than a normal distribution are called leptokurtic. Distributions which are flatter and have lighter tails than a normal distribution are called platykurtic.

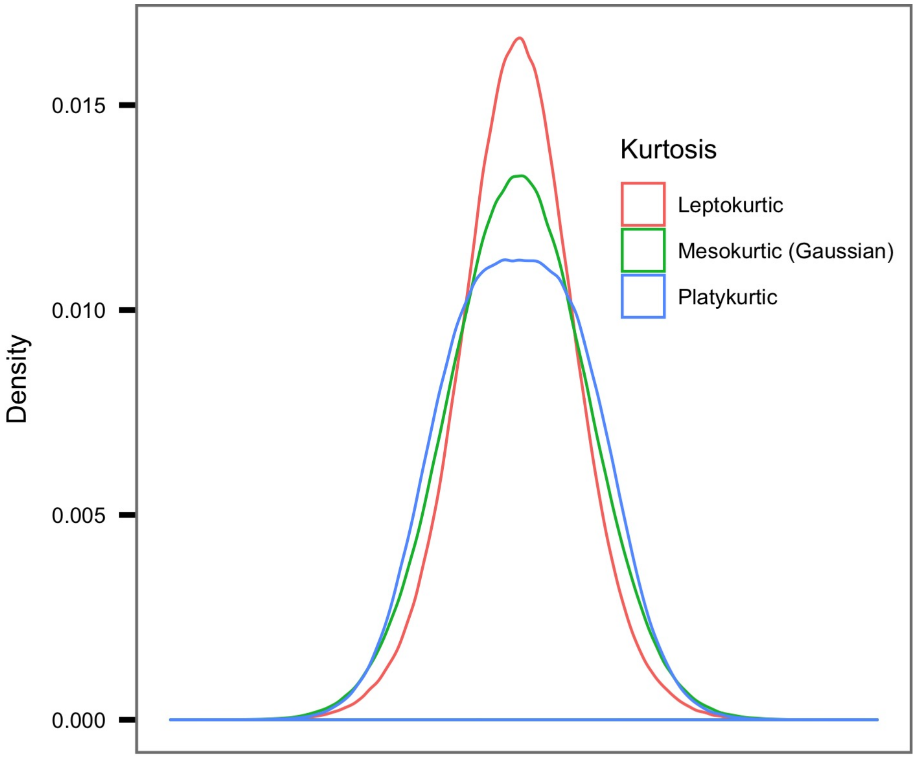
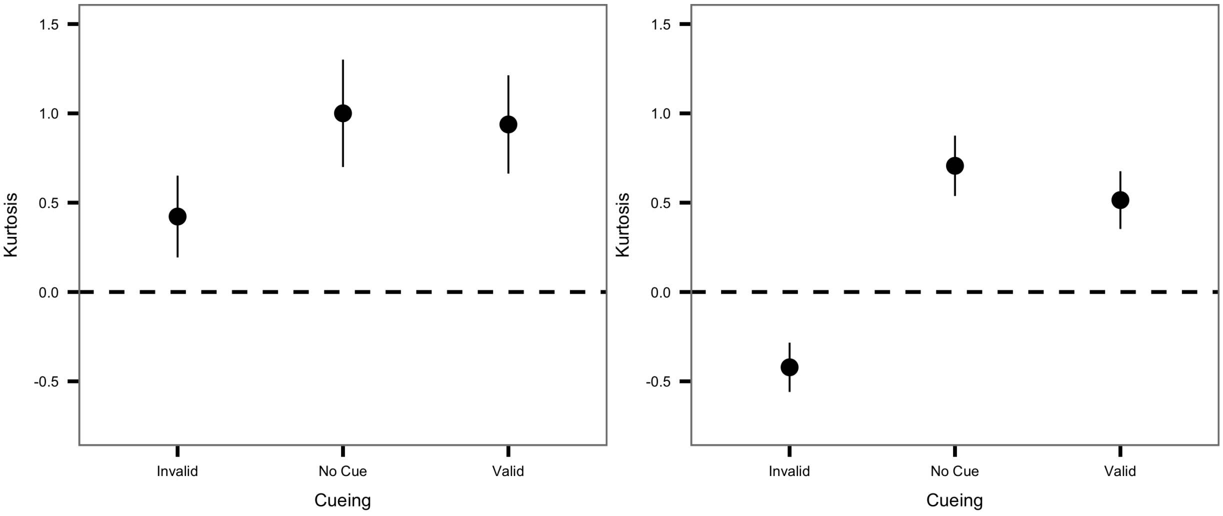


Figure 3.1: Normal distributions (mesokurtic) have an excess kurtosis of zero. Leptokurtic distributions have an excess kurtosis above zero. Platykurtic distributions have an excess kurtosis below zero.

When evaluating kurtosis as a function of cueing on sequential trials in the previous experiments, which is the closest analogy to a single stimulus experiment, we found that cueing affects kurtosis only for predictive cues (Fig. 3.2). One possible explanation for this result is that because predictive cues provide information about target location that is useful, participants' tolerance for false alarms (trials where attention was misdirected on invalid trails) was increased, whereby participants, whether with or without intent, risked making big errors on 20% of the trials in order to make more precise responses on 80% of the trials when the target appeared in the cued location.



(a) 50%, Uninformative, Cues

(b) 80%, Informative, Cues

Figure 3.2: The effect of cueing on kurtosis was not statistically significant on sequential trials in Chapter 2, Experiment 3 for 50% spatial cues (a) , but it was in Chapter 3, Experiment 2 for 80% spatial cues (b).

Since predictive cues and reward both communicate priority about a target or spatial location, it seemed possible that the shape of a reward distribution could have an effect on the shape of an error distribution in an orientation judgement task. Specifically, we wanted to evaluate if we could increase participants' tolerance for false alarms with a 50% cue by pairing them with reward signals that either did or did not highly reward precision and highly penalize imprecision. To achieve this end, we used kurtotic reward distributions.

Consequently, in the present experiments we combined a 50% valid cueing paradigm with kurtotic performance-based rewards. We know that a 50% cue should not affect kurtosis, therefore the research question of interest in these experiments is whether kurtotic rewards can cause a 50% valid cue to have an effect on kurtosis, and hence, evaluate whether attention and reward interact. If reward and attention processes are similar, as they are commonly described to be, we would expect there to be an interaction.

3.2 General Method

The equipment, procedure, and task were the same across all experiments. These experiments only differed in how reward was communicated to participants. This section therefore describes what was similar between experiments. The communication of reward and any other differences are described in the method section of each individual experiment.

3.2.1 Participants

All participants reported normal or corrected-to-normal visual acuity. The experiments were approved by the Office of Research Ethics at the University of Waterloo, and all participants signed informed consent prior to participation.

3.2.2 Stimuli, design and procedure

The experiments were programmed in Python using the PsychoPy library (Pierce, 2007). Stimuli were displayed on a 33 x 26.5 cm CRT monitor with a screen resolution of 1024 x 768 pixels and a refresh rate of 84 Hz. Participants were seated at a viewing distance of 60 cm. All stimuli were presented on a gray background with a luminance of 39.3 cd/m^2. On 20% of the trials the spatial cue was neutral and appeared on both the left and the right sides. On the remaining 80% of trials, the spatial cue was 50% valid and therefore provided no information about the target's spatial location. The experiment took approximately one hour.

The general trial structure and timings are shown in Fig. 3.3. The stimuli were Gabors consisting of sinusoidal, gauss masks (size: 4°; spatial frequency: 4 cycles/deg., contrast: 0.5), a spatial cue consisting of a border of a white square (4.4°x 4.4°) and a response line (4°x 0.07°). Participants were instructed to keep their eyes fixated at the center of the screen and their fingers on the response keys throughout the experiment. A trial started with a fixation cross (1.2°) at the center of the display for 500 ms. The spatial cue then appeared alone for 60 ms followed by the Gabor at a random orientation and appearing randomly 6°to the left or right of the fixation cross. The cue and the Gabor remained together for 60 ms and then disappeared. The spatial cue was therefore on the display for a total of 120 ms. After they disappeared the fixation cross appeared alone for 200 ms and then the response line appeared in the same location the Gabor previously appeared in. Participants were required to make an orientation judgement of the Gabor they just viewed by rotating the response line using the left and right arrow keys on the keyboard. Participants had an unlimited amount of time to make their response and were instructed to be as accurate as possible. Responses were therefore unspeeded. After participants pressed the up key to enter their response, the reward associated with their error (the difference between true orientation and judged orientation) was provided and then the next trial began.

3.2.3 Data analysis

All analyses were conducted in R using the *heplots* (Fox et al., 2014), *nlme* (Pinheiro et al., 2014), *multcomp* (Hothorn et al., 2008), *e1071* (Meyer, Dimitriadou, Hornik, Weingessel, & Leisch, 2014) and *BayesFactor* (Morey & Rouder, 2015) packages. The *ggplot2* package was used to create all plots (Wickham, 2009).

Many of the figures presented are box plots, a standard data visualization. The lower and upper bounds of the 'box' are the first and third quartile of the data. The difference between these values is called the interquartile range (IQR). Outliers are defined as any point that is three or more times the IQR above the third quartile or below the first

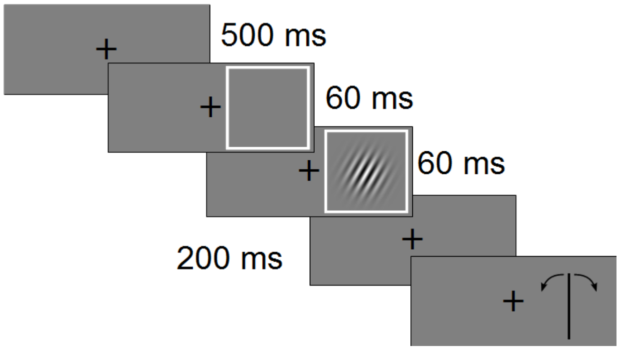


Figure 3.3: General Method (Reward): Participants viewed a fixation cross for 500 ms followed by a spatial cue for 60 ms that could be either valid, invalid or neutral (appearing on both the left and right hand sides). The Gabor then appeared randomly on the left or right side of fixation at a random orientation for 60 ms after which the cue and the Gabor disappeared together. The cue was therefore on the display for a total of 120 ms. After 200 ms of fixation, a response line appeared in the same location as the Gabor and participants were required to make an orientation judgment by rotating the line using the left and right arrow keys on the keyboard. After recording their response by pressing the up key, they received reward based on their error communicated via a piano key with a given pitch (Experiment 1), a set amount of time to wait for the next trial to begin (Experiment 2) or points appearing 1°below the fixation cross for 300 ms (Experiment 3).

quartile and are the points on the box plot. If there are no outliers, the 'error bars' are the maximum and minimum thresholds of the data. If there are outliers, the 'error bar' on the side or sides with outliers is instead 1.5 times the interquartile range.

The error between true orientation and judged orientation on each trial was calculated by subtracting the true orientation from the judged orientation and wrapping it to an interval between -90°and +90°. No effects of bias were found for any condition in any experiment so the analysis of bias is not reported here. We quantified precision as the median, absolute error of the corrected angular difference, which was calculated by subtracting the mean angular difference for each participant in each condition from the signed angular difference on every trial.

3.3 Experiment 1 - Pitch

The purpose of Experiment 1 was to evaluate whether spatial cueing effects are differentially affected by the shape of a reward distribution communicated to participants via variable-pitch, auditory feedback.

3.3.1 Method

Participants

Eighty students participated in exchange for credit applied to a University of Waterloo undergraduate psychology course. There were two reward conditions: coarse and fine. There were 40 participants in the coarse condition and 40 participants in the fine condition.

Stimuli, design and procedure

Participants earned points (not displayed to participants) based on their errors in one of two conditions: coarse and fine. In the coarse reward condition, points were coarsely related to participant errors and in the fine condition, points were finely related to participant errors (Figure 3.4). The fine and coarse curves were calculated from a generalized normal distribution (Eq. 3.1) where the Γ is the gamma function, β defines the shape of the distribution, α the scale (spread), and μ the location (0 for fine and coarse). The shape parameter β for the fine reward condition was set to one and was set to four for the coarse reward condition. The α parameter was fit such that the area under the curve for the fine condition was equal to the area under the curve for the coarse condition. This resulted in an α of 9 in the fine condition and 29.05 in the coarse condition.

$$\frac{\beta}{2\alpha\Gamma(1/\beta)}e^{-(|x-\mu|/\alpha)^{\beta}} \tag{3.1}$$

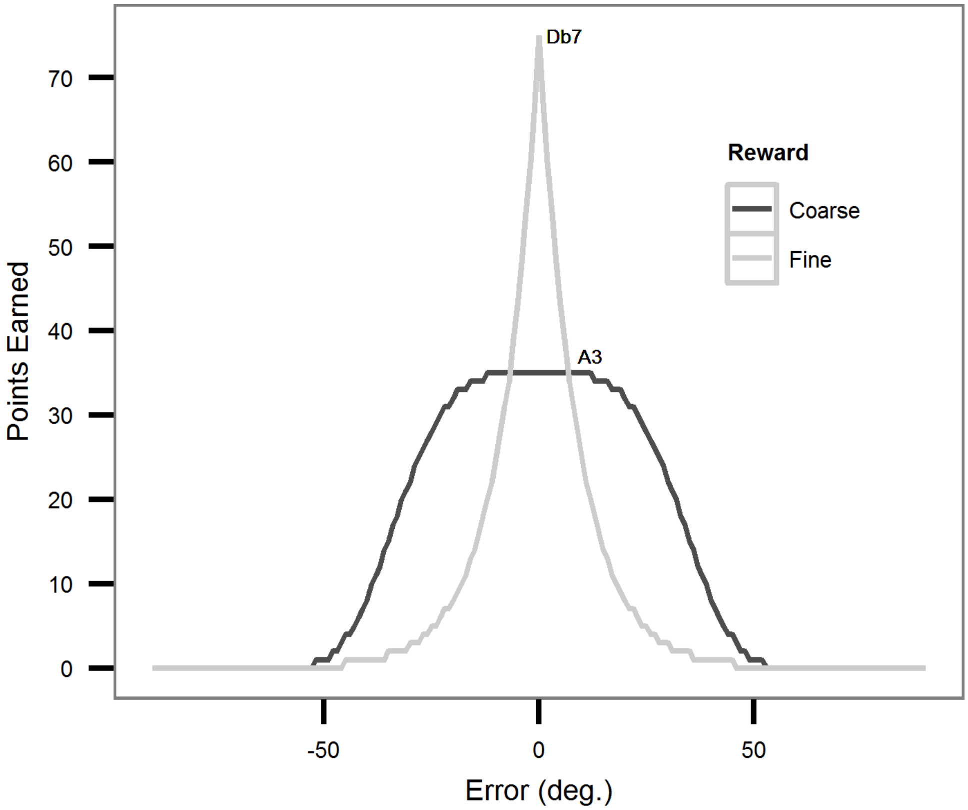


Figure 3.4: Reward distributions in the Fine and Coarse conditions in Experiment 1 (Pitch)

Immediately after making a response, the points earned was communicated auditorily to participants via the pitch of a piano key. Participants were not informed that the pitch of the piano key related to points. They were informed that the pitch of the tone corresponded to their accuracy and that the higher the pitch the more accurate their response was.

The piano key sound bites were taken from the University of Iowa Electronic Music

Studios website where they were trimmed using *Audacity* to an equal length of 300 ms and then normalized to an equal volume using *normalize*.

The experiment consisted of 100 practice trials followed by 5 blocks of 150 experimental trials for a total of 750 experimental trials. Prior to the start of the practice trials, participants did a pitch discrimination test consisting of 15 trials. On each trial, two piano keys were played one immediately after the other and participants were required to indicate whether the second piano key was higher or lower in pitch. If it was higher they pressed the up key and if it was lower they pressed the down key.

3.3.2 Results & Discussion

One participant in the fine condition was removed from the analysis for performance indistinguishable from chance. The average score on the pitch discrimination test was 73.7% (˜11 out of 15 correct).

The omnibus 2 (Reward: coarse vs. fine) x 3 (Cueing: invalid vs. neutral vs. valid) mixed effects ANOVA indicated that the between-subjects main effect of reward on precision was not significant [F(1,77) = 0.579, p = .45], and neither was the interaction between reward and cueing [F(2,154) = 0.284, p = .75]. The main effect of cueing on precision was significant [F(2,154) = 28.575, p <.001, η_p^2 = .27]. The linear Tukey contrasts indicated that precision was lower on invalid trials compared to valid and neutral trials, but that the difference between valid and neutral trials was not significant (Table 3.1).

Contrast	**Estimate** (deg.)	**Z-value**	**P-value**
Neutral - Invalid	-0.88499	-6.533	<.001
Valid - Invalid	-0.89694	-6.621	<.001
Valid - Neutral	-0.01195	-0.088	1.0

Table 3.1: Linear Tukey contrasts on precision between the levels of cueing in Experiment 1 (Pitch).

In order to evaluate whether the absence of a main effect of reward was the result of the variable ability of participants to distinguish between piano key pitches, the analysis was repeated including only those participants who scored 80% or more (12 or more correct) on the pitch discrimination test, which amounted to 36 participants (16 coarse and 20 fine). The main effect of reward on precision was not significant [$F(1{,}34) = 0.001$, $p = .98$].

In summary, the standard effect of a spatial cue on precision (B. Anderson & Druker, 2013; Prinzmetal et al., 1998, 1997) was replicated; however, there were no effects of reward distribution on precision. It is possible that the auditory feedback was too subtle for participants to pick up the reward distribution from and/or it was too easily ignored.

Further, there is nothing inherently rewarding about hearing a piano key so it was perhaps too ambitious to expect participants would treat it as such. Consequently, in Experiment 2 a less subtle and more difficult to ignore reward signal was utilized.

3.4 Experiment 2 - Time

In Experiment 2 a more obvious and difficult to ignore reward signal was utilized. It was hypothesized that undergraduates would be motivated by a reward that allowed them to reduce the length of the experiment if they performed well. Consequently, the reward was communicated via the amount of time that passed between making a response and the start of the next trial.

3.4.1 Method

Participants

Thirty-nine students participated in exchange for credit applied to a University of Waterloo undergraduate psychology course. There were four conditions: related coarse reward, yoked coarse reward, related fine reward and yoked fine reward. There were 10, 10, 10, and nine participants in each group respectively.

Stimuli, design and procedure

As an indicator of reward, the amount of time that passed between trials varied for participants between zero and three seconds in two ways: the shape of the distribution could be either finely or coarsely related to errors as in the first Experiment (Figure 3.5), but also, the timings experienced could either be directly related to their performance or they were the yoked timings from the previous participant in the same reward condition. The yoked timings were included as a control condition in order to rule out that any observed effects were due to the differences in timing independent from the reward they were meant to signal. This resulted in four conditions: related coarse, related fine, yoked coarse, and yoked fine. All participants regardless of condition were informed that the amount of time that passed between trials was related to performance, but in what way was not elaborated. At the end of the experiment participants were asked what they believed the relation between their accuracy and the time delay was.

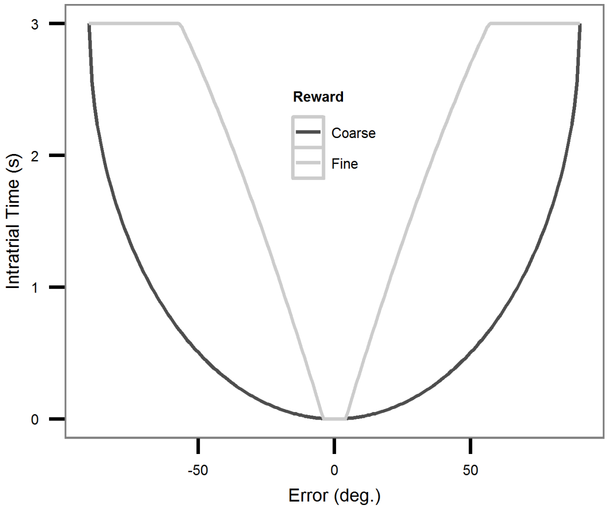


Figure 3.5: Reward distributions in the Fine and Coarse conditions in Experiment 2 (Time)

The number of practice trials was reduced to 20 trials from 100 trials in Experiment 1 to reduce the duration of the experiment below one hour. The experiment therefore consisted of 20 practice trials followed by 5 blocks of 150 experimental trials for a total of 750 experimental trials.

3.4.2 Results & Discussion

One participant in the yoked coarse condition, one participant in the related fine condition, and two participants in the yoked fine condition were removed from the analysis for performance indistinguishable from chance.

The omnibus 2 (Reward: coarse vs. fine) x 2 x (Type: related vs. yoked) x 3

(Cueing: invalid vs. neutral vs. valid) mixed effects ANOVA indicated that only the main effect of cueing on precision was significant [$F(2{,}64) = 11.068$, $p < .001$, $\eta_p^2 = .26$].

Responses to the debriefing question indicated that all participants, including those in the yoked conditions, believed that the time between trials directly related to their performance. Participants in the related conditions correctly reported that the delay between trials was shorter the more accurate they were. Participants in the yoked conditions confabulated a variety of convoluted explanations for how the delay was related to their performance (for instance, one participant was so adamant that they were convinced I was lying to them when I told them it was not related to their performance). Informally, many participants commented that it was unpleasant when the next trial began immediately indicating that the reward structure may have been flawed. For many participants a trial that occurred immediately after the one before or a trial that occurred after a long delay were both dispreferred. It was not anticipated that the trials coming in rapid succession would be unpleasant since previous versions of the experiment without reward had had no delay between trials. Consequently, this reward structure was abandoned in favour of a more directly rewarding and motivating signal.

3.5 Experiment 3 - Points without No Reward condition

In the first two experiments, unconventional, implicit, and subtle reward signals were used operating under the premise that reward effects should be learnable from context in the same way that probability effects are. However, the results demonstrated this may not be the case. Others have reported that reward effects are absent when the rewards are not explicitly related to the task (Jiang et al., 2015). Consequently, in Experiment 3 a more conventional system of directly awarding participants points or money was employed.

3.5.1 Method

Participants

Fifty-two students participated in exchange for credit applied to a University of Waterloo undergraduate psychology course. Twenty-six participants were in the coarse reward condition and 26 participants were in the fine reward condition.

Stimuli, design and procedure

The points were awarded to participants following the same shape of the fine and coarse distributions in Experiment 1 (Fig. 3.4) except the points were scaled from -10 to 60 instead of 0 to 70, and instead of communicating reward via the pitch of a piano key participants were directly rewarded with points displayed on the screen. After a response was made, the number of points that was earned appeared 1° below the fixation spot in black text 0.6° in height. The total score was displayed for the entire duration of the experiment in black text 0.6° in height, 1° above the fixation spot. Finally, as an additional incentive, participants had an opportunity to win a reward on top of the credit that they received for participating, and this was determined by the precision of their orientation judgements. If overall precision was in the top 20% (percentiles were determined from the performance distributions in Experiment 1 for fine and coarse rewards) the participant won a chocolate bar and if it was in the top 10% the participant won five dollars. The projected percentile position, calculated by estimating the final score on each trial, was displayed to participants 2° above the fixation spot either in white text 0.6° in height or via an image of a chocolate bar (3.6a) or a dollar sign (3.6b). Percentile positions in the top 30% and lower were indicated via an integer number between 10 and three (i.e., a seven meant they were in the top 70%). If they were in the top 20% the chocolate bar was displayed and if they were in the top 10% the dollar sign was displayed. Their estimated percentile position was updated on every trial.

(a) Chocolate Bar (b) Dollar Sign

Figure 3.6: The chocolate bar (a) and dollar sign (b) images displayed to participants in Experiments 3 and 4

Participants were not informed that there were different conditions that determined the magnitude of the points that they received and how these were related to their performance. Consequently, participants had no basis to compare the points they were awarded and no prior knowledge about the maximum number of points they could earn for a perfect response. Further, they were also not informed what the high scores were or how many previous participants had won money or a chocolate bar.

3.5.2 Results & Discussion

Three participants from the coarse condition and three participants from the fine condition were removed from the analysis because of a technical snafu. Two participants in the coarse condition and two participants in the fine condition were removed from the analysis for performance indistinguishable from chance.

In the fine condition, participants earned a mean of 17716 points (SD = 3496). In the coarse condition, participants earned a mean of 14840 points (SD = 2084). This difference was significant [Fig. 3.7; $t(32.619) = 3.24$, $p < .05$, $d = 1.0$]. One participant in the fine condition (5%) and two participants in the coarse condition (10%) won five dollars. Three participants in the fine condition (14%) and six participants in the coarse condition (29%) won chocolate bars.

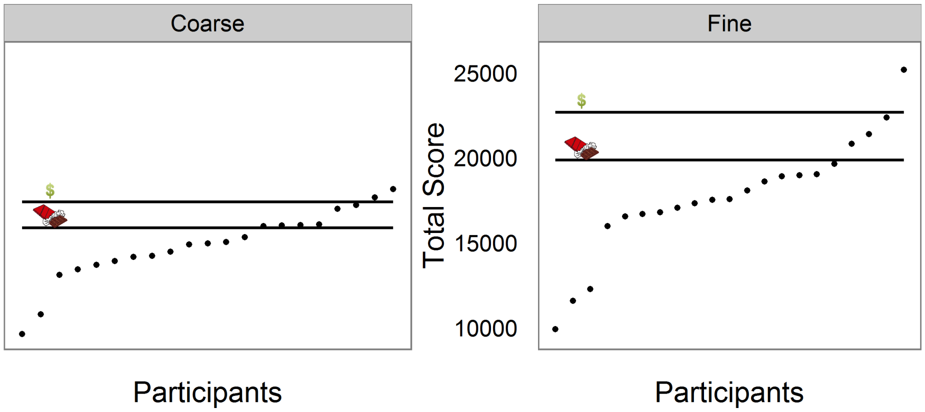


Figure 3.7: Participant scores in the Coarse and Fine conditions in Experiment 3 (Points)

The omnibus 2 (Reward: coarse vs. fine) x 3 (Cueing: invalid vs. neutral vs. valid) mixed effects ANOVA indicated that the between-subjects main effect of reward on precision was significant [$F(1,40) = 5.466$, $p < .05$, $\eta_p^2 = .12$]. Participants were more precise in the fine reward condition than in the coarse reward condition. The main effect of cueing was also significant [F(2,80) = 26.124, p <.001, η_p^2 = .40]. The linear Tukey contrasts indicated that participants were more precise on valid trials than invalid and neutral trials (Table 3.2).

Contrast	**Estimate** (deg.)	**Z-value**	**P-value**
Neutral - Invalid	-0.7189	-3.888	.<.001
Valid - Invalid	-1.3014	-7.038	<.001
Valid - Neutral	-0.5825	-3.150	<.001

Table 3.2: Linear Tukey contrasts on precision between the levels of cueing in Experiment 3 (Points).

The interaction between reward and cueing was significant (Figure 3.8) [F(2,80) = 3.088, p = .05, η_p^2 = .08]. The main effect of cueing was significant in both reward conditions [fine: F(2,40) = 13.35, p = .001, η_p^2 = .40; coarse: F(2,40) = 15.21, p = .001, η_p^2 = .43].

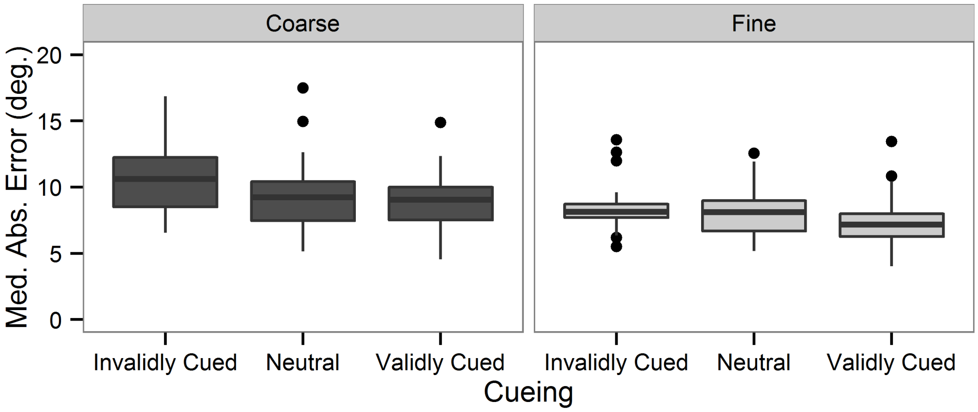


Figure 3.8: Responses were more precise in the fine reward condition. Valid cueing increased precision only in the fine reward condition (light grey) and invalid cueing reduced precision only in the Coarse reward condition (dark grey) in Experiment 3 (Points)

The linear Tukey contrasts indicated that valid cueing increased precision only in the fine condition and invalid cueing reduced precision only in the Coarse reward condition (Table 3.3).

	Fine Reward			Coarse Reward		
Contrast	**Estimate** (deg.)	**Z-value**	**P-value**	**Estimate** (deg.)	**Z-value**	**P-value**
Neutral - Invalid	-0.2748	-1.336	.38	-1.1630	-3.925	.<.001
Valid - Invalid	-1.0266	-4.990	<.001	-1.5761	-5.319	<.001
Valid - Neutral	-0.7519	-3.655	<.001	-0.4131	-1.394	.34

Table 3.3: Linear Tukey contrasts on precision between the levels of cueing in Experiment 3 (Points).

The interaction effect was small, so an additional level of analysis was performed to evaluate it. The Bayes Factors were calculated in order to evaluate whether a model with the interaction was preferred over one without it. We found that the model including the interaction term was the most preferred compared to the model including only the random effect of participant 3.9

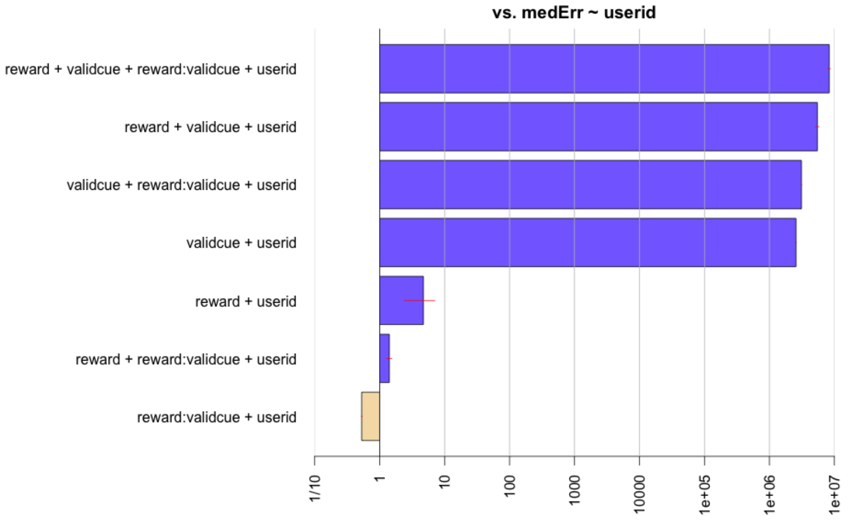


Figure 3.9: The Bayes Factor for all models in Chapter 3, Experiment 3. The model including both main effects and the interaction is the most preferred.

Lastly, we calculated kurtosis to evaluate whether kurtotic performance-based rewards affected the kurtosis of the error distributions as a function of reward and cueing. Kurtosis was calculated using the *e1071* package in R (Meyer et al., 2014). There were no effects on kurtosis [cueing: $F(2{,}80) = 0.369$, $p = .69$; reward: $F(1{,}40) = 1.777$, $p = .19$; interaction: $F(2{,}80) = 1.878$, $p = .16$].

In summary, we replicated the effect of cueing on response precision and demonstrated that precision is greater when rewards are finely related to performance. Further, we have shown preliminary evidence that kurtotic rewards interact to affect cueing, namely that valid cues improve performance only when they are fine and invalid cues hurt performance only when they are coarse. We did not find any direct effects on kurtosis itself.

3.6 Experiment 3 - Points with No Reward condition

The interaction effect in Experiment 3 was small so the experiment was repeated on a new cohort of participants.

3.6.1 Method

Participants

Sixty students participated in exchange for credit applied to a University of Waterloo undergraduate psychology course. Twenty participants were in the coarse points condition, 20 participants were in the fine points condition, and 20 participants were in the no points condition.

Stimuli, design and procedure

The fine and coarse reward conditions were identical to those in Experiment 3. The no reward condition is new in Experiment 4.

3.6.2 Results & Discussion

The omnibus 3 (Reward: coarse vs. fine vs. none) x 3 (Cueing: invalid vs. neutral vs. valid) mixed effects ANOVA indicated that the between-subjects main effect of reward on precision was significant [$F(2,57) = 5.768$, $p < .01$, $\eta_p^2 = .17$]. The linear Tukey contrasts indicated that responses were more precise in the Fine condition than the Coarse condition, and more precise in the No Reward condition than the Coarse condition (Table 3.4).

Reward Shape

Contrast	**Estimate** (deg.)	**Z-value**	**P-value**
Coarse - Fine	1.7461	3.090	.<.01
None - Fine	0.1837	0.325	.94
None - Coarse	-1.5624	-2.765	<.05

Table 3.4: Linear Tukey contrasts on precision between the levels of reward in Experiment 4 (Points).

Cue Status

Contrast	**Estimate** (deg.)	**Z-value**	**P-value**
Neutral - Invalid	-0.5962	-3.973	.<.001
Valid - Invalid	-0.8814	-5.874	<.001
Valid - Neutral	-0.2853	-1.901	.14

Table 3.5: Linear Tukey contrasts on precision between the levels of cueing in Experiment 4 (Points).

The main effect of cueing was also significant [$F(2{,}114) = 17.46$, p <.001, $\eta_p^2 = .23$]. The linear Tukey contrasts indicated that responses were less precise on invalid trials than neutral and valid trials. There was no difference between valid and neutral trials (Table 3.5).

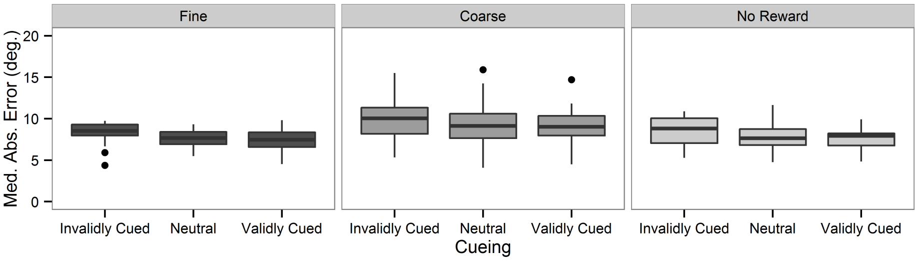


Figure 3.10: Responses were more precise in the fine reward condition than the coarse reward condition, and more precise in the no reward condition than the coarse reward condition. Responses were also more precise on neutral and valid trials compared in invalid trials. There was no interaction between reward and cueing in Experiment 4. (Points)

The interaction between reward and cueing was not significant [Fig. 3.10; $F(4,114) = 0.17$, $p = .95$]. The Bayes Factors for all possible models were calculated. We found that the model including only the main effects of cueing and reward was the most preferred compared to the model including only the random effect of participant 3.11

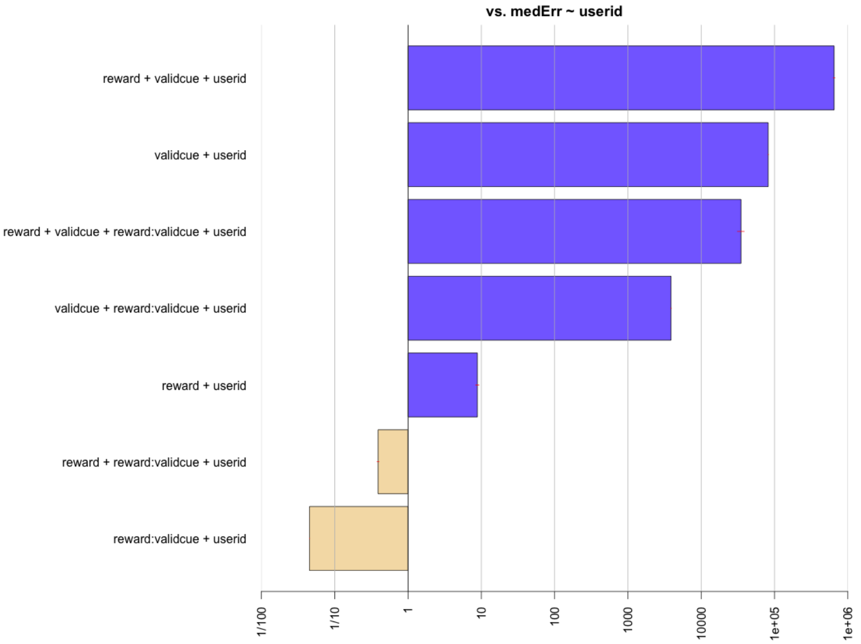


Figure 3.11: The Bayes Factor for all models in Chapter 3, Experiment 4. The model including only both main effects was the most preferred.

To explain the difference in the interaction effects of Experiments 3 and 4 several possibilities were considered. It is possible that the no reward condition diluted the interaction effect. Therefore, the analysis was repeated excluding the no reward condition. Still; the interaction effect was still absent. Another possibility is that the effect was small.

The two experiments were combined to increase power and the analysis was repeated. An omnibus 2 (Reward: coarse vs. fine) x 3 (Cueing: invalid vs. neutral vs. valid) mixed effects ANOVA for precision indicated that the main effect of cueing was significant [$F(1,99) = 94.515$, $p < .001$, $\eta_p^2 = .49$] and the main effect of reward was significant [$F(2,99) = 9.335$, $p < .001$, $\eta_p^2 = .16$]. The interaction was not significant [$F(2,99) = 1.084$, $p = .34$].

An analysis of kurtosis on the combined dataset was also performed. An omnibus 2 (Reward: coarse vs. fine) x 3 (Cueing: invalid vs. neutral vs. valid) mixed effects ANOVA for kurtosis indicated that no effects were significant [cueing: $F(1,99) = 1.490$, $p = .23$; reward: $F(2,99) = 1.526$, $p = .22$; interaction: $F(2,99) = 2.509$, $p = .09$]. The Bayes Factor for the model containing only the interaction and the random intercept of participant was very slightly above one (1.04).

Bayes factors greater than one indicate that the model is preferred more than the model it is being compared to (Jeffreys, 1961), in this case the model containing only the random effect of participant. A Bayes factor greater than one for the effect of the interaction on kurtosis taken together both with the anova result (p-value less than .1) and with the interaction effect on response precision in Experiment 3 is converging evidence of the possibility of a subtle interaction between reward and cueing. In the combined data set, there is a difference in kurtosis for fine rewards, but not for coarse rewards (fine: 4.8 (valid) vs. 3.5 (invalid); coarse: 3.4 (valid) vs. 3.5 (invalid)), and critically, kurtosis is increased on valid trials for fine rewards only. Similarly, in Experiment 3 valid cueing improved precision only for fine reward distributions. One possibility is that the effect of variable performance-based reward on orientation judgments depends on how well the reward distributions are learned and this in turn affects how and whether they interact with spatial cueing. Repeating the experiment on a cohort of trained participants may provide a clearer analysis of the interaction.

3.7 Discussion

Participants completed a Posner spatial cueing (1980), orientation judgment task in which they received rewards related to their performance. A spatial cue preceded the target on 80% of the trials and was 50% valid in three experiments that differed only in the method by which reward was communicated to participants. We consistently replicated the facilitation effect of spatial cues at short SOAs (reviewed in Carrasco, 2011) in all three experiments demonstrating the robustness of this effect. The results of the present experiments differed only in the effects of reward.

Almost all perceptual experiments with human subjects manipulating reward use rewards that are monetary. Monetary rewards have a concrete value associated with them and are explicit. Motivated by the hypothesis that reward effects can be implicit in the same way that probability effects are we initially chose reward signals that could be interpreted implicitly by perceptual systems. Prior work on auditory statistical learning has demonstrated that infants and adults are able to segment non-linguistic tone sequences by monitoring sound bites for statistical regularities (Saffran, Johnson, Aslin, & Newport, 1999) so it seemed reasonable to hypothesize that participants could implicitly learn the reward distributions communicated via auditory tones. However, we did not find an effect of auditory reward distributions in Experiment 1 even when we confined analysis to those participants who performed well on the pitch discrimination test. The most probable explanation for our results is that the auditory tones were not sufficiently related to the task so participants ignored them as prior work has demonstrated that reward effects are absent when they are not explicitly related to the task (Jiang et al., 2015). It is also possible, given the subtleness of the association, that there was not enough time in the experiment for participants to learn the distributions. A training phase prior to the experimental trials may have been necessary. Lastly, as there is nothing inherently rewarding about an auditory tone, expecting participants to treat this association as rewarding may have been too ambitious.

Attempting to make the rewards more relevant and motivating we used a reward signal related to the timing of the experiment in Experiment 2. Answers to the debriefing question demonstrated that the differences in the amount of time between trials was noticed and the relation was correctly identified where present. This indicates that, in contast to Experiment 1, the reward signal was not ignored in Experiment 2. However, we did not anticipate that participants would find rapid succession trials unpleasant.

The results of the first two experiments suggest that rewards with untrained participants that are not obviously relevant do not affect perception. Consequently, we relaxed our goals and used a reward that was familiar and obvious, points. In order to further motivate participants we also provided them with an opportunity to win an additional reward for performing exceptionally well. We found effects of reward in this experiment and a replication. Orientation judgments were more precise when rewards were finely related to performance than when they were coarsely related to performance. This effect parallels response time observations from experiments using discrete and monetary rewards (B. A. Anderson et al., 2011; Della Libera & Chelazzi, 2009; Failing & Theeuwes, 2014; Hickey et al., 2010b; Kiss et al., 2009; Krebs et al., 2010; Lee & Shomstein, 2014; Muhle-Karbe & Krebs, 2012; Raymond & OBrien, 2009; Rutherford et al., 2010; Serences, 2008) and demonstrates that it is not necessary for rewards to be discretely associated with some objects and not others to have effects.

The effect of the interaction between reward and cueing was consistent, but statistically elusive. We found that response precision was improved on valid trials only for the fine reward distribution in Experiment 3, but not in Experiment 4 or the combined analysis. However, the combined analysis did reveal a possible interaction effect on kurtosis: kurtosis was greater on valid trials than invalid trials only for the fine reward distribution. When considered together, this is converging evidence that leptokurtic reward distributions change how we process and respond to spatial cues, but that the extent to which they do so may rely on how well the relation between reward and response precision is learned and that association may need to be represented strongly in order for kurtosis effects to emerge. As well, because it is the fourth moment of a distribution, kurtosis benefits exponentially from larger datasets compared to medians, which is a possible account for its absence when the data from each experiment is analysed separately. When the data is combined, more of the noise in how well the relation was learned is averaged.

In Chapter 2 we demonstrated that spatial cueing effects rely on how we monitor our environment for statistical regularities and consequently assign importance to events (valid cues) that are statistically regular. At the start of this chapter we suggested that reward may also serve as a signal for communicating importance. We have demonstrated that fine performance based rewards affect response precision similar to spatial cues, but also that they may interact with spatial cueing to affect kurtosis on valid trials similiar to predictive spatial cues. One possible explanation is that predictive cues and fine performance-based rewards cause changes in the efficiency with which sensory information is evaluated. This would be consistent with attentional theories that emphasize noise exclusion and reductions in sensory uncertainty (Lu et al., 2002; Shiu & Pashler, 1994).

In order to evaluate this hypothesis, we developed a gaze-contingent paradigm that allowed us to equate stimulus viewing time across cue and reward conditions. Visual search efficiency may affect the time course of locating and making decisions about targets. As such, in experiments where the stimulus is on the display for a fixed duration, as with the experiments in Chapters 2 and 3, there may be more time to process a stimulus when there is more importance allocated to its spatial location and this importance is amplified by fine performance-based rewards. Further, it is possible that interaction effects between reward and attention may be increased when there are detectable changes in rewards within participants. This is the purview of Chapter 4.

Chapter 4

Overt and covert orienting of attention with spatial cueing and reward, a look at eye-tracking

4.1 Introduction

So far we have demonstrated that when multiple stimuli must be remembered, valid cueing improves precision only when the stimuli must be consolidated at the same time (Chapter 2), the predictiveness of a spatial cue changes the shape of the error distribution (Chapter 2), and leptokurtic rewards increase orientation judgement precision and may interact to affect kurtosis on valid trials (Chapter 3).

One account for these results is that reward increases vigilance resulting in a general increase in sensitivity whereas attention increases visual search efficiency resulting in differences in viewing times, the time during which the relevant features to the task are distinguishable and in the visual field, when stimuli are transient and displayed for a fixed duration. Such an account would explain the interaction between reward and attention on response precision and the effect of fine performance-based rewards on the kurtosis of valid trials by increasing vigilance to valid cues, and the presence of an interaction between memory and attention as visual search efficiency would have the largest effect when there are distractors. Increased sensitivity in response to rewards can also account for response time effects previously reported (e.g., Hickey et al., 2010a), namely that sensitivity increases enhance stimuli salience.

In order to disentangle these different mechanisms we modified the experiments in Chapter 3 to fit an eye movement paradigm. In the present experiment viewing time was fixed by controlling the offset of the stimulus with participant eye movements. The stimulus contrast was reduced to a threshold where it was difficult to determine orientation while fixated at center and the stimulus remained on the display until the participant fixated at its location. The number of possible stimulus locations was also increased to six to slow participants away from ceiling. The hypotheses for the present experiment are elaborated on separately for reward and attention in the subsections that follow.

4.1.1 Reward

We have shown that reward effects on precision may not be independent of cueing and that the shape of the error distribution is more peaked on valid trials for fine rewards as indicated by kurtosis. Prior work discussed in the introduction to Chapter 3 would suggest that the effect on precision could be explained by a direct effect of reward on perception via attention; however, it is unclear what attention is oriented towards when rewards are not object or feature based and this does not account for the possible interaction of fine rewards and cueing on precision and kurtosis. One possible explanation for these results is that reward increased participants' tolerance for false alarms (invalid trials): fine rewards encouraged participants to risk orienting to the wrong location because the pay off when it was the right location was a noticeably substantial amount of points compared to being only slightly imprecise. Essentially, we suggest that rewards enhanced participants' vigilance towards cues.

If rewards cause changes in vigilance to valid cues we would expect no effect on precision when viewing time is fixed since the opportunity to increase viewing time as a result of vigilance is eliminated. Consistent with this hypothesis, Hickey, Chelazzi and Theeuwes (2010b) demonstrated that in a rewarded, visual search task where the stimuli remained on the display until response, response times to previously rewarded targets were reduced, but accuracy was unaffected.

Further, if participants are more vigilant to valid cues we would expect the frequency of first saccades to validly cued locations to be greater for fine rewards, but for there to be no effect on fixation response time. In support of this hypothesis, reward has previously been shown to affect saccade probability (vigilance), but not saccade response times. Camara, Manohar and Husain (2013) were investigating the effect of past monetary reward or penalty of a given location on eye movements and button-press responses. They measured the effect of previous reward (yoked to spatial location) on free choices (indicated by eye movements and button presses) between stimuli in different locations and on eye movements to distractors. They demonstrated that rewarded locations were chosen more frequently (increased vigilance to those locations), but there were no differences in free choice, saccade response times between locations that had previously been rewarded and penalized.They also demonstrated that saccades to distractors in previously rewarded locations were more frequent than those in previously penalized locations; however, there were no differences in saccade response times.

4.1.2 Eye Movements

With respect to cueing, effects of overt orienting are well documented (reviewed in Kowler, 2011). Prior work has demonstrated for instance that microsaccades around the locus of fixation are not random, but are clustered in the direction of the object of covert attention, and that although this occurred only approximately 25% of the time, responses to targets in the presence of microsaccades were better (Hafed & Clark, 2002). It has also been demonstrated that target detection was better in locations that coincided with saccades and that it is not possible to attend to spatial locations that are different from saccade destinations (Hoffman & Subramaniam, 1995). Further, eye movements have been shown to be proceeded by shifts in visual attention (Hoffman, 1998).

The existing literature on overt attention does not discuss combinations of spatial cues and overt orienting as all of the focus has been on evaluating their effects on covert orienting. However, there is no reason to believe they would be different than covert orienting since covert attention has been shown to proceed saccades, and taken together, these results would suggest that response times to fixate stimuli in validly cued locations should be faster than response times to invalidly cued locations.

Further, in the experiments reported in Chapter 2 and Chapter 3 invalid trials were found to be significantly different than uncued trials. However, this was not always the case for valid trials. The abrupt onset of the Gabor on uncued trials is arguably a spatial cue itself, and because participants are not misdirected from fixation on uncued trials the "distance to travel" to the target location is shorter. The difference in viewing time between valid trials and uncued trials is therefore smaller than the difference between invalid and uncued trials. This further supoorts the hypothesis that differences in viewing time account for the effects of spatial cues.

4.1.3 Present Experiment

In sum, the purpose of the present experiment was to evaluate the hypothesis that reward effects are effects on vigilance and spatial cueing effects are effects on visual search efficiency. Prior work would suggest that fixation response times should be unaffected by reward and faster on validly cued trials. Further, if viewing time is fixed, reward and cueing effects on precision should both be absent as there is no affordance for additional viewing times resulting from increases in vigilance and visual search efficiency. Finally, increased vigilance to valid cues should cause more frequent first saccades to validly cued locations.

4.2 Method

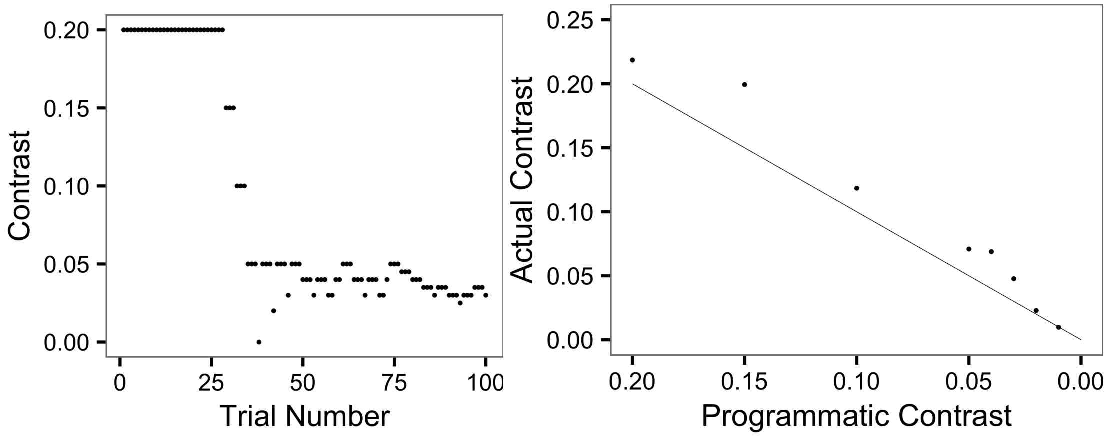
4.2.1 Participants

Seventy-four undergraduate and graduate students participated in exchange for credit applied to a University of Waterloo undergraduate psychology course (17) or $10 (57). All participants reported normal or corrected-to-normal visual acuity, and had not previously participated in the experiments reported in Chapter 3. The experiments were approved by the Office of Research Ethics at the University of Waterloo, and all participants signed informed consent prior to participation.

4.2.2 Stimuli, design, apparatus and procedure

The experiment was programmed in Python using the PsychoPy library (Pierce, 2007). Stimuli were displayed on a 36.5 x 27.5 cm Viewsonic Graphics Series G90fB CRT monitor with a screen resolution of 1024 x 768 pixels and a refresh rate of 85 Hz. Participants were seated at a viewing distance of 62 cm. All stimuli were presented on a gray background with a luminance of 32.2 cd/m^2. On 20% of the trials there was no spatial cue. On the remaining 80% of trials, the spatial cue was 50% valid and therefore provided no information about the target's spatial location. The experiment took approximately one hour.

The experiment began with an adaptive, "3 down, 1 up" staircase procedure for scaling the contrast to equate visual search difficulty across participants to a detection rate of 80% (Leek, 2001). The purpose of the staircase procedure was to reduce the stimuli contrast to a threshold where it was detectable, but that orientation discrimination was difficult unless the stimulus was fixated. All participants started at a contrast of 0.2 and this remained constant for the first 25 trials so that participants could familiarize themselves with the protocol. The contrast was then adjusted across the following 125 trials for the first 26 participants, but this was reduced to 75 trials for the remaining 48 participants as 75 trials was sufficient for the end contrast to stabilize. There was no physical separation between these two types of trials: participants completed 150/100 consecutive trials. The mean end contrast was 0.039 (Fig. 4.1a; SD = 0.016). Figure 4.1b shows the relation between the programmatically defined contrast and the actual contrast as measured with a photometer.



(a) Participant Contrasts

(b) Actual Contrast

Figure 4.1: Example of one participant's contrast staircase (a), and the relation between programatically defined contrast and actual contrast as measured by a photometer (b) in Chapter 4, Experiment 1

A staircase trial began with a single Gabor consisting of a sinusoidal, gauss mask (size: 4°; spatial frequency: 4 cycles/deg) appearing for 60 ms on the display in one of the six locations possible during the following experimental trials (30°, 90°, 150°, 210°, 270°and 330°radially) at a radius of 6°from the center of the display. After the Gabor disappeared participants were required to click with the mouse in the location where they remembered it appearing. Following their click a white dot (0.2°in size) appeared indicating the location of their click along with a black dot (0.2°in size) indicating the correct location. A click was considered to have occurred in the correct location if the radial error (difference between the click and stimulus bearing) was less than 23°.

If the participant made three consecutive correct responses the contrast was reduced by a staircase size that started at 0.05. If an incorrect response was made the contrast was increased by a staircase size that also started at 0.05. The staircase size was reduced (Table 4.1) each time the participant's accuracy reversed twice in a row (i.e., correct-incorrect-correct or incorrect-correct-incorrect).

Reversal Number	0	2	4	6	16	26	32	40	46
Staircase Size	0.05	0.03	0.02	0.01	0.005	0.0025	0.0015	0.0010	0.0005

Table 4.1: Step size decrements after each reversal.

Following the staircase procedure the participant was fitted with the head-mounted Eyelink II (`http://www.sr-research.com/EL_II.html`) and it was calibrated using a 13 point calibration. Both eyes were tracked during calibration and the eye with the lowest degree of error was selected for tracking throughout the experiment. The order of the positions was randomized and the calibration procedure was set to repeat the first point as the last point. Calibration was triggered automatically with a pacing interval of 500 ms. Validation was done manually, and in cases where participants had difficulty controlling their blinking, calibration was done manually as well. If the error during validation greater than 0.6°the calibration procedure was repeated until it was less than 0.6°. If after several attempts the calibration was still less than 0.6°, the experiment was ended and the participant was informed they would still receive their remuneration, but would not be able to complete the experiment (14 participants; most due to inability to control excessive blinking, one for eye makeup). Head tracking was turned on as there was no chinrest so participants were personally responsible for keeping their head as still as possible. The importance of doing so was demonstrated to participants by showing that head position was lost when the sensors on the corners of the monitor were out of the visual field of the camera on the headset. Eye-movement tracking occurred at a sampling rate of 250 Hz.

The experimental procedure was based off of Chapter 3, Experiment 4: participants made orientation judgements of Gabors that were preceded by a 50% valid spatial cue on 80% of the trials and a bilateral cue on 20% of the trials. Rewards were performance based and could be either finely or coarsely related to performance. Differences in the present experiment were: six stimulus locations instead of two, contrast was dynamic, the stimulus was slightly smaller size, participants triggered the offset of the stimulus rather than it disappearing on its own, neutral trials were uncued trials rather than the cue appearing in all locations, and reward was manipulated within-subjects as well as between-subjects.

The experiment began with 25 practice trials to allow participants the opportunity to adjust to locating the stimulus, using their eyes to trigger the offset of the stimulus, and to using the response keys. The practice trials were followed by two blocks of 250 experimental trials. At the end of the first block participants were allowed the opportunity for a rest break. Most chose to immediately start the next block, but for those who opted for a rest break the eye tracker was re-calibrated when they were ready to recommence. Otherwise a scheduled drift correction, consisting of looking at a single white dot at the center of the screen, occurred instead. If the error between center and eye position was large (more than 3 cm radially from center) the eye tracker was re-calibrated. Drift corrections were otherwise done on an as-needed basis throughout the experiment. Need was determined when triggering failed despite the participant fixating the target. There were an average of three such corrections required for each participant (SD = 3). Participants who wore corrective lenses required more drift corrections than participants who did not. The tolerance between eye position and stimulus position to trigger a trial or stimulus offset was set to a 100 pixel (approximately 3.2°) radius around the center of the stimulus.

A trial (Fig. 4.2) began with a white fixation dot (0.3°) at the center of the screen. Participants were instructed to look at it to start the trial and so a trial did not begin until they fixated the central fixation point. Once fixated, the spatial cue consisting of a white square outline (size: 3.3°; line thickness: 0.14°) appeared if it was a cued trial in one of the six possible locations for 60 ms and then disappeared. After it disappeared (or immediately after triggering the trial on uncued trials) the Gabor appeared in either the same (valid) or different (invalid) location and participants were instructed to locate it by looking at it. Once fixated it disappeared and participants were presented with fixation for 200 ms. Following this, participants were prompted to estimate what angle the Gabor was at by rotating a response line (3°x 0.07°) appearing in the same location as the stimulus. A response was made by using the left and right arrow keys on the keyboard to rotate the line and pressing the up key to enter a response. After pressing the up key the correct orientation displayed as a white line with the same dimensions as the response line, reward was signaled (next section), and then the next trial began.

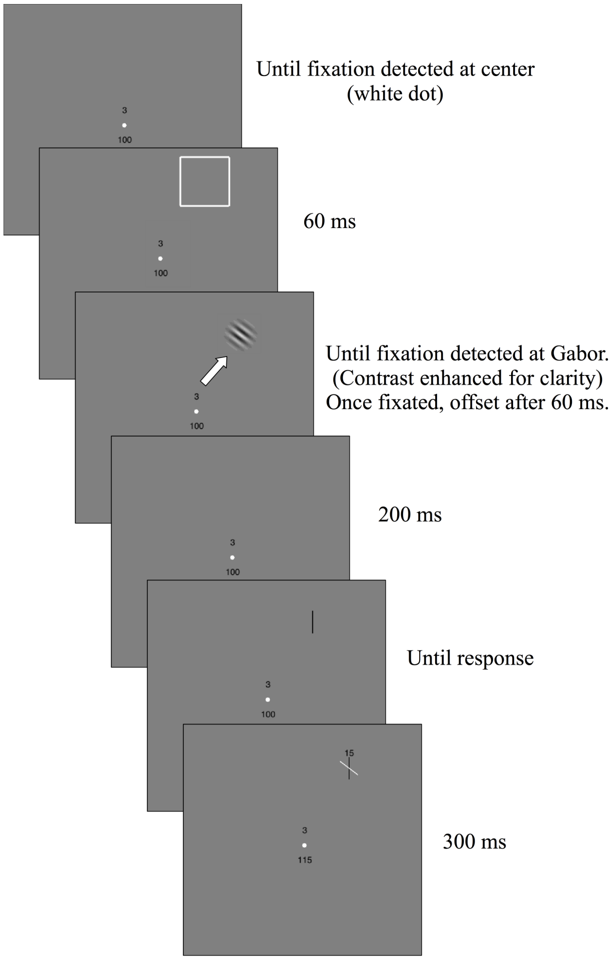


Figure 4.2: Chapter 4 Procedure: A trial began when participants fixated at the white dot at the center of the display. Once triggered a spatial cue consisting of a white square appeared on the display for 60 ms on cued trials (80% of the time) and was 50% valid. Following the cue, a Gabor appeared in the same (valid) or different (invalid) location and remained on the display until participants fixated at its location. Once fixated, the Gabor remained on the display for 60 ms and then disappeared. Following 200 ms of just fixation (white dot) participants were promoted to indicate the orientation of the Gabor they previously viewed by rotating a response line using the left and right arrow keys. Once a response was entered by pressing the up key, the correct orientation was indicated via a white line and points were awarded according to the condition (fine, coarse or none) and their response accuracy. Their percentile position (displayed above the fixation dot) was also updated. This feedback was displayed for 300 ms.

Reward

Point rewards were the same system implemented in Chapter 3, Experiment 3, with the exception that the positions were changed to accommodate the fact that participants were not always expected to be fixated at the center of the screen. Consequently, the number of points earned on an individual trial was displayed 3.3°above the center of where the stimulus appeared, the total cumulative score was displayed 1°below the fixation dot and percentile position was displayed 1°above the fixation dot. Further, there were three between-subjects groups defined by the type of reward they were exposed to and in what order: one group earned fine rewards in the first block and coarse rewards in the second block, one group earned coarse rewards in the first block and fine rewards in the second block, and one group earned no rewards in the first block and fine rewards in the second block. Percentile positions were determined based on overall performance in Chapter 3, Experiments 3 and 4 (averaged high and low for the first two groups).

4.2.3 Data analysis

The 11 trials preceding a drift correction were removed from the analysis because drift corrections within blocks were performed on an as needed basis as indicated by a deterioration of the calibration. The number of trials to remove was determined visually by plotting the mean fixation response time by the number of trials until a drift correction and selecting the point where response time was no longer stable (Figure 4.3). This resulted in a 3.39% loss of the data.

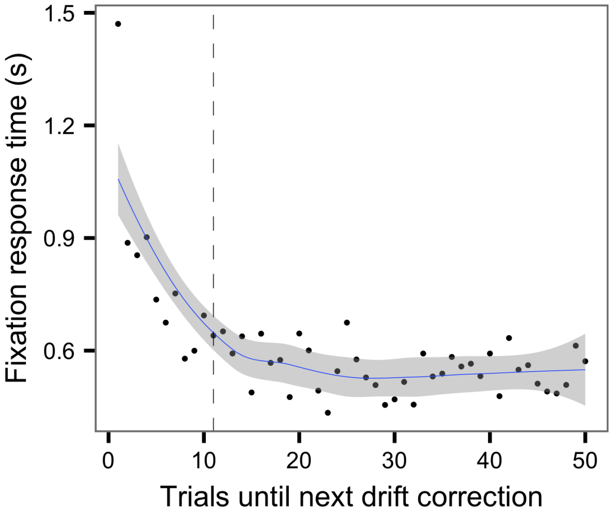


Figure 4.3: Method for removing trials proceeding a drift correction: selected visually at the point where response time was no longer stable

All analyses were conducted in R using the *heplots* (Fox et al., 2014), *nlme* (Pinheiro et al., 2014), *multcomp* (Hothorn et al., 2008), *e1071* (Meyer et al., 2014) and *BayesFactor* (Morey & Rouder, 2015) packages. The *ggplot2* package was used to create all plots (Wickham, 2009).

Many of the figures presented are box plots, a standard data visualization. The lower and upper bounds of the 'box' are the first and third quartile of the data. The difference between these values is called the interquartile range (IQR). Outliers are defined as any point that is three or more times the IQR above the third quartile or below the first quartile and are the points on the box plot. If there are no outliers, the 'error bars' are the maximum and minimum thresholds of the data. If there are outliers, the 'error bar' on the side or sides with outliers is instead 1.5 times the interquartile range.

The error between true orientation and judged orientation on each trial was calculated by subtracting the true orientation from the judged orientation and wrapping it to an interval between -90°and +90°. No effects of bias were found for any condition in any experiment so the analysis of bias is not reported here. We quantified precision as the median, absolute error of the corrected angular difference, which was calculated by subtracting the mean angular difference for each participant in each condition from the signed angular difference on every trial.

4.3 Results

Fourteen participants were not included in the analysis as they did not complete the experimental portion following the staircase procedure resulting from an inability to calibrate the eye tracker. Five participants whose median errors were greater than two standard deviations from the overall median were removed from the analysis (more than approximately 10°).

4.3.1 Precision

The Bayes Factors for all possible models were calculated in order to determine the most preferred model. We found that the most preferred model compared to the model for predicting the precision of angular responses did not include any effects of cueing. It did contain the main effect of group, the main effect of reward, and the interaction between group and reward 4.4. Thus, when viewing time is held constant, cues do no affect accuracy, but reward appears to. However, the analysis reported below indicated that the effect of reward was due only to a within-subjects effect that was the result of participants performing better in the second block than the first block due to practice effects.

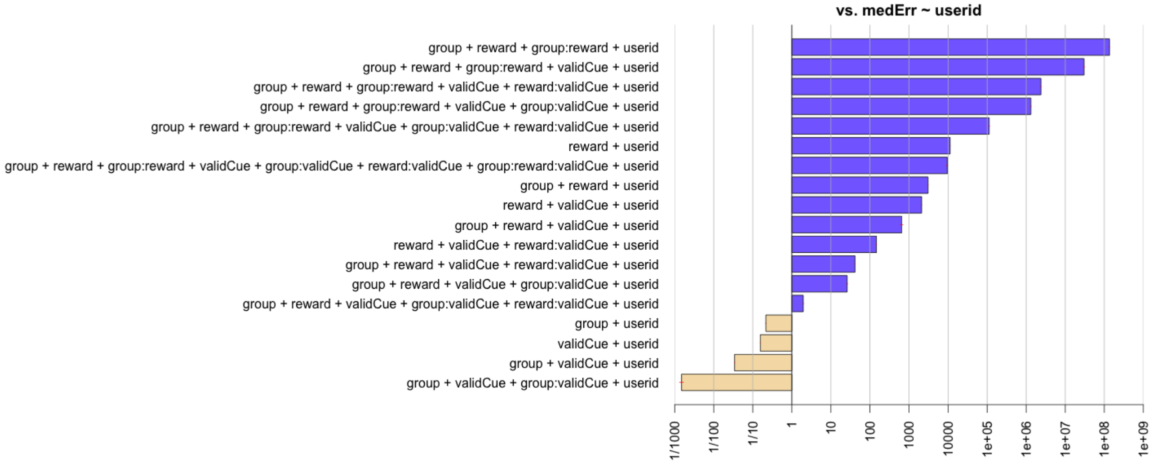


Figure 4.4: The Bayes Factor for all possible models for precision in Chapter 4. The model including only the main effects and interaction between group and reward was the most preferred.

Supporting the absence of cue effects in the highest Bayes Factor model, an omnibus 3 (Group: fine then coarse vs. coarse then fine vs. none then fine) x 3 (Reward: coarse vs. fine vs. none) x 3 (Cueing: invalid vs. neutral vs. valid) mixed effects ANOVA indicated that the main effect of cueing was not significant [$F(2{,}104) = 2.632$, $p = .08$], and neither were the interactions between reward and cueing [$F(4{,}156) = 0.614$, $p = .65$], and group and cueing [$F(4{,}104) = 0.851$, $p = .50$]. The three-way interaction was also not significant [$F(2{,}156) = 0.576$, $p = .56$].

With respect to the variables included in the preferred model, the main effect of group was not significant [$F(2{,}52) = 0.476$, $p = .62$]; however, the main effect of reward [$F(2{,}156) = 14.618$, $p < .001$, $\eta_p^2 = .16$]. and the interaction between group and reward [$F(1{,}156) = 23.499$, $p < .001$, $\eta_p^2 = .13$] were significant.

The analysis was repeated for the effect of reward to apportion between between-subjects effects and within-subjects effects. A between-subjects analysis of reward across the first block indicated that when viewing time is fixed, precision was no longer greater for fine rewards compared to coarse and no rewards. The main between-subjects effect of reward was not significant [$F(2{,}52) = 0.1.326$, $p = .27$].

The within-subjects effect of reward, however, was significant for all three between-subjects groups [fine then coarse: $F(1{,}19) = 10.19$, $p < .01$, $\eta_p^2 = .35$; coarse then fine: $F(1{,}17) = 6.934$, $p < .05$, $\eta_p^2 = .29$; none then fine: $F(1{,}16) = 9.249$, $p < .01$, $\eta_p^2 = .37$].

Visual inspection of Fig. 4.5 indicates that precision in the reward condition of the second block was better than precision of the reward condition in the first block indicating that practice effects may explain the significant effect of within-subjects reward.

This alternative was evaluated by repeating the analysis while controlling for the effects of trial using a linear mixed effects model. No effects of reward were preserved when the effect of time was included [fine then coarse: $t(9.494\text{e}3) = -0.324$, $p = .75$; coarse then fine: $t(8.699\text{e}3) = -0.324$, textitp = .39; none then fine: $t(8.208\text{e}3) = 1.49$, $p = .14$].

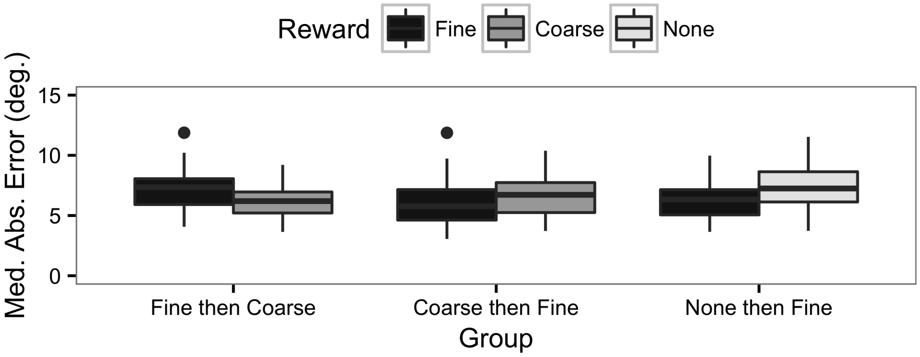


Figure 4.5: The within-subjects effect of reward in Chapter 4 was explained by practice effects: participants made more precise responses in the second block than in the first block leading to perceived within-subjects effects of reward that were eliminated when the effect of trial was included in the analysis. In sum, there were no effects of any factor on precision.

In summary, equating viewing time across all conditions eliminated the effects of cueing and reward on precision.

4.3.2 Fixation Response Time

The precision results provide preliminary evidence that when viewing time is fixed the effects of reward and attention are eliminated, suggesting that spatial cueing effects may result from the increased viewing time afforded by improved efficiency in locating targets. Indeed, an omnibus 3 (Group: fine then coarse vs. coarse then fine vs. none then fine) x 3 (Reward: coarse vs. fine vs. none) x 3 (Cueing: invalid vs. neutral vs. valid) mixed effects ANOVA for the median log of fixation response times indicated that the main effect of cueing was significant [F(2,104) = 306.476, p <.001, η_p^2 = .85]. Response times to locate the target on validly cued trials were faster than on invalidly cued and uncued trials (Table 4.2).

Contrast	**Estimate** (log(s))	**Z-value**	**P-value**
Neutral - Invalid	-0.05438	-2.047	.10
Valid - Invalid	-0.59002	-22.214	<.001
Valid - Neutral	-0.53564	-20.166	<.001

Table 4.2: Linear Tukey contrasts on fixation response times between the levels of cueing in Chapter 4.

The main effect of group [F(2,52) = 3.721, p <.05, η_p^2 = .13] and the main effect of reward [$F(2{,}156) = 7.259$, $p <.001$, $\eta_p^2 = .09$] were also significant. However, the main between-subjects effect of reward (first-block only) on fixation response times was not significant [$F(2{,}52) = 2.972$, $p = .06$], and when controlling for practice effects by including a factor for time in a linear mixed effects model, the within subjects effect of reward was not significant for any group [fine then coarse: $t(9.493e3) = 1.455$, $p = .16$; coarse then fine: $t(8.699e3) = 0.021$, $p = .98$; none then fine: $t(8.208e3) = -1.802$, $p = .07$]. As such, the main effect of reward can be explained by participants getting faster over time.

With respect to the main effect of group, the Linear Tukey contrasts indicated that fixation response times were faster in the no reward followed by fine reward condition than the coarse reward followed by fine reward condition [*Estimate* = -0.13238, $Z = -2.692$, $p <.05$]. There was no difference in fixation response times between the no reward then fine reward condition and the fine reward then coarse reward condition [*Estimate* = -0.05016, $Z = -1.046$, $p = .55$] or between the fine reward then coarse reward and coarse reward then fine reward conditions [*Estimate* = -0.08222, $Z = -1.741$, $p = .19$].

No interactions were significant [group and cueing: $F(4{,}104) = 1.451$, $p = .22$; group and reward: $F(1{,}156) = 2.163$, $p = .14$; reward and cueing: $F(4{,}156) = 0.542$, $p = .71$; group, reward and cueing: $F(2{,}156) = 0.073$, $p = .93$].

Taken together with the results reported for precision, we have shown that the absence of spatial cueing effects on precision were not the result of an ineffective spatial cue as we found faster fixation response times on valid trials. These results also suggest that reward distribution does not affect either the precision of orientation judgements or response times to locate targets when viewing time is controlled.

4.3.3 First Saccades

Differences in fixation response time can result via one of two routes: differences in the time to locate the stimulus and differences in the time to initiate the first saccade away from central fixation. In order to distinguish between these two, we evaluated the effects of reward and cueing on the time to initiate the first saccade following the onset of the target.

A linear mixed effects model including the main effects of time, reward and cueing, and all interactions between the levels of reward and cueing and the random effect of participant indicated that only the time to initiate the first saccade for uncued trials was affected [$t(8.590e3) = 14.476$, $p <.001$]. First saccade times were slower on uncued trials (invalid: 160ms; uncued: 305ms; valid: 156ms) as these trials did not have an event that prompted the participant to locate the target as there was no spatial cue prior to the target appearing on the display. Consequently, differences in fixation response time between validly cued and invalidly cued trials are not the result of participants taking longer to initiate the first saccade away from fixation, but rather result from participants scanning the display on invalid trials to locate the target and not having to do so on validly cued trials. Indeed, participants initiated more saccades on invalidly cued trials (2.29) compared to uncued (1.52) and validly cued trials (1.3) [Table 4.3; $F(2{,}108) = 142.6$, $p < .001$, $\eta_p^2 = .73$].

Contrast	**Estimate** (log(s))	**Z-value**	**P-value**
Neutral - Invalid	-0.76293	-12.48	<.001
Valid - Invalid	-0.98351	-16.09	<.001
Valid - Neutral	-0.22058	-3.61	<.001

Table 4.3: Linear Tukey contrasts on the mean number of start saccades between the levels of cueing in Chapter 4.

Lastly, if participants are more vigilant to valid cues we would expect the frequency of first saccades to validly cued locations to be greater for fine rewards. In order to evaluate this hypothesis we calculated the absolute vale of the difference between the angular bearing of the cue and the angular bearing of the first saccade. The majority of the differences were small (less than 10 degrees) indicating that the majority of the time participants made saccades towards the cues, so frequency was operationalized by the z-score of the differences grouped by participant, reward and cue validity. The proportion of trials in each group where the absolute value of the z-score was less than one was evaluated in a

3 (Group: fine then coarse vs. coarse then fine vs. none then fine) x 3 (Reward: coarse vs. fine vs. none) x 3 (Cueing: invalid vs. neutral vs. valid) mixed effects ANOVA. The interaction between reward and cueing was significant [$F(2,104) = 3.768$, $p < .05$, $\eta_p^2 = .08$]. For both fine (valid: 9% irregular; invalid: 11% irregular) and coarse rewards (valid: 9% irregular; invalid: 11% irregular), irregular (differences more than one standard deviation from the mean) saccade angular bearings were more frequent on invalid trials; however, the opposite was true for no rewards (valid: 11% irregular; invalid: 8% irregular) indicating that although the effect was not isolated for fine rewards, there is some evidence that reward in general increases vigilance towards valid spatial cues.

4.3.4 Pupil Diameter

Pupil diameter has previously been associated with attention and arousal (Bradley, Miccoli, Escrig, & Lang, 2008; Koivisto, Hyönä, & Revonsuo, 2004) and so we evaluated the effects of reward and attention on pupil diameter to further demonstrate the effectiveness of the spatial cue despite the absence of effects on precision and to evaluate whether the reward distributions were detected despite having no effects on behavioural responses. Pupil diameter was evaluated by subtracting mean pupil diameter on the display preceding the cue (start of the trial until cue triggered by fixating at center) or reward (stimulus offset until response entered) from the maximum pupil diameter on the display following the cue (onset of stimulus until stimulus offset triggered by participant) or reward (300ms after a response was entered until the next trial was triggered by the participant fixating at center).

A linear mixed effects model including factors for time, reward and the random effect of participant revealed that pupil diameter did not differentially change between pre- and post- rewards in the fine then coarse rewards group [156 (fine) vs. 166 (coarse), *t(9.429e3)* = 0.331, p = .74]. However, in the coarse then fine group, pupil diameter changed less for coarse rewards (166) than fine rewards (265) [*Estimate (coarse)* = -99.1016, *t(8.050e3)* = -3.201, p <.01] and in the no reward then fine condition, pupil diameter changed less for no rewards (210) than fine rewards (367) [*Estimate (none)* = -156.93128, *t(7.954e3)* = -5.9981, p <.001]. Consequently, although there were no behavioural effects of reward, it was processed to some extent as evaluated by differences in pupil diameter pre- and post-rewards.

With respect to attention, a one-way within-subjects ANOVA (cued vs. not cued) for change in pupil diameter indicated that pupil diameter changed more on cued trials (1162) than uncued trials (978) [$F(2,54) = 11.88$, p <.01, $\eta_p^2 = .18$]. It is likely that pupil diameter changes on uncued trials result from the onset of the stimulus acting as a weak spatial cue.

4.4 Discussion

Spatial cueing effects on response time and accuracy are incredibly robust, and here we've eliminated them when viewing time was fixed. The possibility that the cue was not effective at orienting attention was ruled out by the observation that participants' fixation response times to the stimuli were faster on validly cued trials and this can be explained by taking less time to locate the stimulus as first saccade times were unaffected by cueing, and more saccades were made on invalid trials when attention was misdirected compared to uncued and valid trials. These results suggest that the robust spatial cueing effects on response time and accuracy seen in many attentional paradigms reflect additional viewing time that succeeds a valid cue when the stimulus is presented for a fixed duration or the viewing time is terminated by the participant's response. This observation is consistent with a visual search efficiency account of spatial attention: visual search is more efficient when target locations are known and this affords more time to consolidate the stimuli into memory. Further, most participants fixation response times were fast and in the range of express saccades (Fischer & Ramsperger, 1984). Fisher and Ramsberger describe an express saccade as goal directed eye movements that occur rapidly. This would suggest that most eye movements in our experiment were planned during the presentation of the cue alone to achieve the goal of fixating the Gabor as quickly as possible.

Inconsistent with a salience account of reward, we found no effects of reward on fixation response times or first saccade times, nor did we find effects of precision. The possibility that the reward signal was not effective was ruled out by pupillary responses that were affected by reward. These results provide evidence that describing reward effects as effects on attention may not be an accurate explanation for reward effects. If reward effects were effects on attention than we would have expected to find faster fixation response times for fine rewards, whereas, fixation response times were faster in the group that received no rewards compared to the group that received coarse rewards first. One possibility is that the points on the display were visually distracting and that this mitigated reward effects on fixation response times. Consequently, if the experiment were repeated with rewards that were signaled in a way different from visually displaying them it is possible we might find reward effects on fixation response times. However, we did find that the frequency of irregular saccade angular bearings toward spatial cues was greater on invalid trials for the rewarded conditions, but was greater on valid trials for the no reward conditions providing some evidence that reward may increase vigilance to valid cues.

Implications for our understanding of attention are discussed in the General Discussion.

Chapter 5

General Discussion

In 1890, William James stated that everyone knew what attention was. However, 126 years later, there is not a strong consensus about what attention is. This largely reflects the observation that its nature depends on the experimental context and task. Consequently, it has been described using a variety of terms and metaphors, and is frequently used as a black box tool of mass explanation in Cognitive Psychology. Even when researchers create models of attention (e.g., Fig. 5.1) there are multiple nodes for attentional processes in what is meant to be a single model for attention. The impression then is that everything in Cognitive Psychology that is **not** clearly **not** attention, such as perception, memory or decision making, **is** attention.

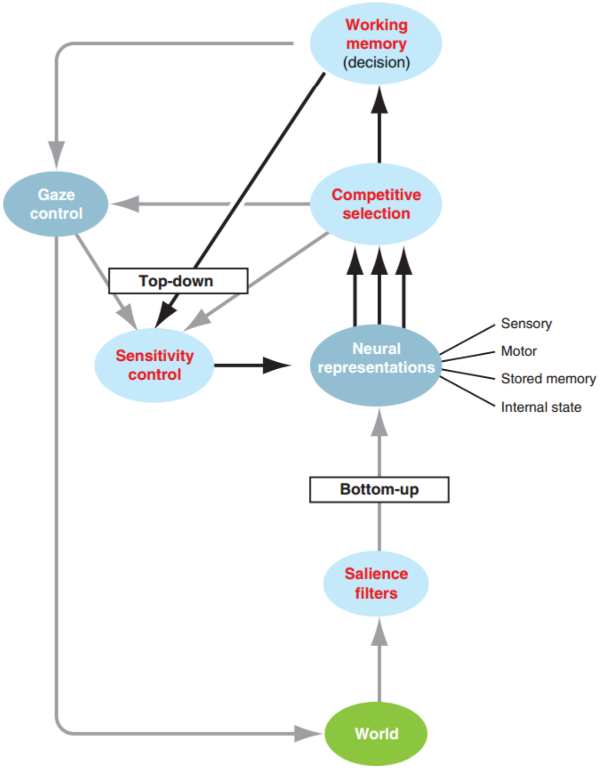


Figure 5.1: One example of a model of attention where there are multiple nodes for different attentional processes (Knudsen, 2007).

Even in domains where attention is not the primary focus, attention is frequently "borrowed" to describe experimental observations. A Google Scholar search returns results with nearly every permutation of the words memory, attention and decision making in article titles. Oppenheimer and Kelso (2015) for instance suggest, in the context of Query Theory, that "principles of memory and attentional processes can explain observed anomalies in evaluations of choices" and Shipstead, Harrison and Engle (2015) state that "the ability to engage attention in a controlled manner is a critical aspect of working memory capacity". It would seem then that attention has its hand in many pots. But perhaps attention is not a module unto itself that acts on every aspect of cognition? This was the starting point for this thesis: attention is used to explain much and consequently consensus is missing, and there are few instances of attention manipulated together in the same tasks its used to explain.

The purpose of this thesis therefore was to evaluate the effects of attention in the context of memory and reward manipulations and ultimately demonstrate how these systems relate and whether they are separable with regards to visual perception. We evaluated over ten experiments how some of the effects described as attention are not necessarily attention, but are a property of the systems required to complete the tasks (i.e., memory and reward systems) and are related to visual search efficiency and vigilance. Essentially, we endeavored to demonstrate whether attention may not necessarily be an independent jack-of-all trades, but may simply be an emergent property of how the human brain processes the external world in general.

We presented ten experiments that evaluated the independence or dependence of attention with memory (Chapter 2) and reward (Chapter 3) and one experiment evaluating visual search efficiency and vigilance as an explanation for these results (Chapter 4). I elaborate on them in the sections that follow.

5.1 Attention & Memory

In Chapter 2 we presented five experiments that were an extension of memory work by Liu and Becker (2013) investigating the nature of consolidation into visual short term memory. Participants made orientation judgements about circluar gratings at random orientations that appeared either together (simultaneous) or were preceded or followed (sequential) by a distractor grating. The predictiveness of the cue as well as the temporal position of the cue on sequential trials was manipulated across experiments. We demonstrated that predictive and non-predictive spatial cues worsened precision on invalid trials regardless of memory condition and improved precision on valid trials only on simultaneous trials demonstrating that attention and memory have interacting effects on perceptual judgements. We also found that cueing effects on model-free precision were the result of affects on guessing for non-predictive cues (Experiments 3 & 5; 50% valid) and the result of model-based precision for predictive cues (Experiments 2 & 4; 80% valid).

The experiments reported in Chapter 2 expanded on previous work in attention and memory by investigating their effects when they are manipulated in the same task. Previous findings have demonstrated that orientation judgements to Gabors that were followed by a spatial cue are improved compared to Gabors that were not post-cued (Sergent et al., 2013) and that this effect also occurs with multiple stimuli (A. M. Murray et al., 2013). Pack, Klein and Carney (2014) also demonstrated that signal enhancement, a strictly perceptual theory of attention, was insufficient to explain cueing effects of transient stimuli. The results of these findings contribute to this body of literature by expanding the findings of Sergent et al. (2013) and Murray et al. (2013) to include the effects of pre-cues. Further, our results also provided the first replication of the effect of working memory load on guessing in an orientation judgement task. Lastly, our use of analytical tools that are not traditionally employed to describe effects of attention is new. The use of the mixture model allowed us to elaborate on the effects of the predictiveness of spatial cues in a way that has not been done historically and enabled us to demonstrate that the allocation of spatial attention is flexible and not all-or-none.

Taken together, these results suggest that when the information is available memory systems integrate knowledge about statistical information in our environment in order to allocate processing resources that are limited by our biology (such as the number of neurons or the glucose available) in the most efficient way possible. An efficiency account for these results does not require the existence of an independent module for attention and suggests that what we observe as attention in such experiments may simply be a property of how our brain maximizes the efficiency of its processes.

An important criticism of this work, however, is that the absence of an effect of valid cues on performance on Sequential trials may have resulted from including cues on only

50% of the trials. Sequential trials were complicated by SOAs that were different depending on whether the target was the first or second stimulus. Although we demonstrated that the result of the cue was the same regardless of its temporal placement in a trial, the interaction between the differing SOAs and the cues presence only 50% of the time may have added significantly more noise in interpreting cues compared to Simultaneous trials. On Sequential trials, the cues may not have reduced uncertainty about target location to the extent that they did on Simultaneous trials because the positions of both stimuli were not revealed simultaneously. As such non-predictive cues on Simultaneous trials were not uninformative as they indicated that the target was only 16.67% likely to be in each of the other three locations whereas on Sequential trials the locations were revealed separately introducing more uncertainty about the likelihood the target would appear in the cued location.

5.2 Attention & Reward

In Chapter 3, we extended the experimental protocol by Anderson and Druker (2013) to include a manipulation of performance-based rewards that were defined by their kurtosis. Participants made orientation judgements of Gabors that appeared on either the left or right side of fixation and were preceded by a spatial cue that was 50% valid. Participants received rewards via an auditory tone at a specific pitch (Experiment 1), variable delays between trials (Experiment 2), and points (Experiments 3a and 3b) at magnitudes that were distributed across the range of possible errors in either a leptokurtic (fine) or platykurtic (coarse) way. Consistent with work demonstrating that reward effects are absent when rewards are not explicitly related to the task (Jiang et al., 2015), we found that rewards needed to be explicit and obvious in order to have effects. We also found slight but converging evidence that attention and reward may interact and that precision was improved for fine reward distributions.

Prior work investigating the effects of reward have used discrete, monetary rewards that were associated with specific stimuli or stimuli features (Della Libera & Chelazzi, 2009; Kiss et al., 2009; Krebs et al., 2010; Lee & Shomstein, 2014; Muhle-Karbe & Krebs, 2012; Raymond & OBrien, 2009; Rutherford et al., 2010; Serences, 2008) Our results expand on these findings to include the effects of rewards that are variable and depend on the precision of participant responses. Further, reward experiments typically evaluate response times or frequencies to rewarded stimuli or locations, or on stimuli that remain on the display until a response is made (e.g., visual search). The experiments in Chapter 3 afforded the opportunity to evaluate the effects of reward on stimuli that are transient and with a response metric that has more resolution. By expanding the study of reward to include effects on precision closer parallels to real world contexts can be made since it is not typically how quickly we respond, but how well we respond that matters in the real world. A possible implication for instance is that finely tuned rewards are more likely to encourage favourable behaviours than ones that are less variable. For instance, a coach that provides generic feedback for most game outcomes and is highly negative for extreme outcomes would improve player performance to a lesser extent than a coach that provides exceptionally positive feedback for excellent performance and becomes stricter as players deviate from excellence.

Finally, in Chapter 4 we presented an eye movement experiment that equated stimulus viewing time across all conditions. The motivation for this experiment was the hypothesis that the effects observed in Chapter 3 may be explained by a visual search efficiency and vigilance account of reward and attention. The task was fairly similar to the points experiment (Experiments 3 and 4) in Chapter 3 with the exception that there were six possible locations and participants controlled the offset of the stimulus by fixating at its location. We demonstrated that when viewing time was fixed there were no effects of attention and reward on precision despite faster fixation response times on valid trials and pupillary responses that were differentially affected by reward. These results are consistent with the results reported in Chapter 2 that uninformative spatial cues do not affect precision, but affect guessing. In the gaze-contingent experiment in Chapter 4 there was little opportunity for guessing. If the experiment were repeated with an informative cue, we might expect then to find cueing effects consistent with the observation in Chapter 2 that informative cues affect precision. Further participants made fewer irregular saccades (saccades with an angular bearing more than one standard deviation farther from the cue angular bearing) towards cues in the rewarded conditions compared to the unrewarded condition supporting a vigilance hypothesis of performance-based rewards.

The contribution of this experiment to the experimental literature on spatial cueing is fairly substantial. Spatial cueing effects are incredibly robust and it is exceptionally rare to fail to replicate them. Here we have done so by equating viewing time, which suggests that the effects of spatial cues on response times and precision can largely be explained by additional viewing time for stimuli that appear on the display for a fixed duration. However, given the weight of the evidence in favour of cueing effects, this result should be replicated. We would also need to repeat the experiment as is, but with a fixed stimulus display time that is not gaze contingent to evaluate whether the length of time the stimulus is on the retina is indeed longer for validly cued trials.

Another limitation to the experiments in Chapters 3 & 4 is that we did not include a training phase like many of the experiments discussed in the introduction to Chapter 3. The results of our experiments therefore must be interpreted with caution as it is possible that they may be different, possibly larger or more conclusive with respect to interaction effects, if conducted with trained participants. It is possible for instance that there are consistent interaction effects, but that they are difficult to detect with untrained participants. It is also possible that there may be effects of reward in the eye movement experiment if the participants are trained with the reward distributions prior to the experimental trials. Replicating the study with a training phase may provide additional insights into the mechanisms of performance based reward distributions and their effects on orientation judgments, and would also allow for a stronger evaluation of how changing the distributions affects response precision.

5.3 Conclusions

In the present thesis, ten experiments were presented that investigated the interaction of attention with memory and reward systems. We demonstrated that attention and memory interact to affect the precision of orientation judgments, performance-based rewards improve precision when they are finely related to performance and may increase vigilance to valid cues, and that the effects of spatial cues can be eliminated by equating viewing time across all conditions. Taken together, these results suggest that what we call attention may be a property of how our brains maximize the efficiency with which we processes our environment.

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Appendices

Custom R Functions

I have included the custom functions that I wrote during the analysis of the data presented in this thesis as they are not publicly available in a published package.

Mixture Model

The following code includes functions that I developed in R to fit the mixture model used in Chapter 2.

```
#Estimated starting parameters

phi.hat <- function(data) {

  n<-length(data)


  LL <- function(par, x) {

    -sum(log(exp(par[2]*cos(2*x-par[1]))/(pi*besselI(par[2],0))))

  }
```

```
  vmmle<-optim(c(0,3), LL, x = data)


  muo_hat<-vmmle$par[1]


  nq_max<-vmmle$par[1]+3*pi/8
  nq_min<-vmmle$par[1]-3*pi/8
  NQ1<-data[data>nq_max]
  NQ2<-data[data<nq_min]
  nq<-length(NQ1)+length(NQ2)
  po_hat<-(n-(4*nq))/n
  if(po_hat<0){
    po_hat<-0.5
  }
  #Initial estimate for kappa
  kappao_hat<-vmmle$par[2]


  phi.hat<-c(po_hat, muo_hat, kappao_hat)
  return(phi.hat)
}
```

```
#MLE of pfvm+(1-p)fu

mixedfit<- function(data) {


  e<-data*pi/180


  p0<-phi.hat(e)


  LL <- function(par, x) {
    -sum(log(par[1]*exp(par[3]*cos(2*x-par[2]))/(pi*besselI(par[3],0))+(1-par[1])*1/pi))
  }


  #Minimizing the negative sum (i.e. maximizing the log-likelihood function,
     MLE)
  result<-optim(p0, LL, x = e, method = "L-BFGS-B", lower=c(0,-pi/2,0.1),
     upper=c(1,pi/2,Inf))


  mu<-round(result$par[2],2)
  kappa<-round(result$par[3],2)
  sigma<-round(sqrt(-log(besselI(result$par[3],1)/besselI(result$par[3],0))),2)
```

```
  g<-round(1-result$par[1],2)


  fn<-function(x) {
    result$par[1]*exp(result$par[3]*cos(2*x-result$par[2]))/(pi*besselI(result$par[3],0))+
      (1-result$par[1])*rep(1/pi,length(x))
  }
  dorig<-hist(e,plot="FALSE",20)
  kstest2<-ks.test(dorig$density, fn(dorig$mids))
  kstestl<-ks.test(dorig$density, fn(dorig$mids),alternative="l")
  kstestg<-ks.test(dorig$density, fn(dorig$mids),alternative="g")
  kstest<-c(kstest2$p.value,kstestl$p.value,kstestg$p.value)
  cor<-max(kstest)


  params<-list("mu" = mu, "kappa" = kappa, "sigma" = sigma,"g" = g, "cor" = cor)


  return(params)


}
```

Eyelink II Ascii Parser

I developed the following function for parsing the ASCII files produced by the Eyelink II into something readable by R.

```
## =============================================================================
## Eyelink II ASCII data file parser
## By Christie Haskell, 28-07-2015 (v.1)
## =============================================================================

#Inputs:
#dirASC - the directory where the ascii files are located
#dirPar - the directory where you want the resulting data frame to be saved
#fileName - the filename of the ascii file you wish to parse

#Outputs:
#eyePos - a dataframe of the eye event data for fixations and saccades

ASCparse<-function(dirASC,dirPar,fileName) {
  fileLines<-readLines(paste(dirASC,fileName,sep="")) #Read in the file lines
```

```
#Row number of first TRIALID 1

rowStart<-which(grepl("TRIALID 1", fileLines))[1]


#Remove all header information

fileLines.ns<-fileLines[c(rowStart:length(fileLines))]


#Remove all lines containing:

fileLines.rmIndex1<-which(!grepl("RECCFG", fileLines.ns))

fileLines.ns1<-fileLines.ns[fileLines.rmIndex1]


fileLines.rmIndex2<-which(!grepl("GAZE_COORDS", fileLines.ns1))

fileLines.ns2<-fileLines.ns1[fileLines.rmIndex2]


fileLines.rmIndex3<-which(!grepl("MODE", fileLines.ns2))

fileLines.ns3<-fileLines.ns2[fileLines.rmIndex3]


fileLines.rmIndex4<-which(!grepl("START", fileLines.ns3))

fileLines.ns4<-fileLines.ns3[fileLines.rmIndex4]


fileLines.rmIndex5<-which(!grepl("PRESCALER", fileLines.ns4))
```

```
fileLines.ns5<-fileLines.ns4[fileLines.rmIndex5]

fileLines.rmIndex6<-which(!grepl("PUPIL", fileLines.ns5))
fileLines.ns6<-fileLines.ns5[fileLines.rmIndex6]

fileLines.rmIndex7<-which(!grepl("EVENTS", fileLines.ns6))
fileLines.ns7<-fileLines.ns6[fileLines.rmIndex7]

fileLines.rmIndex8<-which(!grepl("SAMPLES", fileLines.ns7))
fileLines.ns8<-fileLines.ns7[fileLines.rmIndex8]

#Remove \t
fileLines8<-gsub("\t", " ", fileLines.ns8)

#Samples index
samplesIndex<-which(grepl("^[0-9]{6,}", fileLines8) & !grepl("MSG",
   fileLines8))

#Create trial id variable
trialidRow<-which(grepl("TRIALID", fileLines8))
```

```
lastSample<-length(fileLines8)
nSamples<-trialidRow[2:length(trialidRow)] -
    trialidRow[1:length(trialidRow)-1]
nSamples<-c(nSamples,lastSample-trialidRow[length(trialidRow)])
trialnum<-rep(c(1:25,1:250,1:250),nSamples)
blocknum<-rep(c(rep(0,25),rep(1,250),rep(2,250)),nSamples)

#Add trialnum to lines
fileLines.tn<-paste(trialnum,blocknum,fileLines8,sep=" ")

#Samples
samples<-fileLines.tn[samplesIndex]
samples2<-substr(samples, 1, 40)

#If contains ".  ." then trackloss trial
tLindex<-which(grepl("\\. \\.",samples2))
trackLosses<-samples2[tLindex]
if (length(trackLosses) > 0) {
  trackLosses2<-gsub("0\\.0.*","0.0",trackLosses)
  trackLosses3<-gsub(" \\. ","na",trackLosses2)
```

```
  trackLosses4<-gsub("0\\.0","na",trackLosses3)
  trackLosses.df<-read.table(text=trackLosses4,header=FALSE)
  names(trackLosses.df)<-c("trialnum","blocknum","time","X","Y","pupilDim")
  trackLosses.df$eventType<-"TRACKLOSS"
  trackLosses.df$eye<-"na"
}

samples3<-samples2[-tLindex]
samples4<-sapply(samples3,function(x) strsplit(x," +"))
samples.df<-as.data.frame(matrix(unlist(lapply(samples4,function(x)
   x[1:6])),nrow=length(samples4),ncol=6,byrow=T))
samples.df<-as.data.frame(lapply(samples.df,function(x)
   as.numeric(as.character(x))))
names(samples.df)<-c("trialnum","blocknum","time","X","Y","pupilDim")
samples.df$eye<-"na"
samples.df$eventType<-"SAMPLES"

#Start Saccades
ssaccLinesIndex<-which(grepl("SSACC", fileLines.tn))
ssaccLines<-fileLines.tn[ssaccLinesIndex]
```

```
ssacc.df<-read.table(text=ssaccLines,header=FALSE)
names(ssacc.df)<-c("trialnum","blocknum","eventType","eye","time")

#End Saccades
esaccLinesIndex<-which(grepl("ESACC", fileLines.tn))
esaccLines<-fileLines.tn[esaccLinesIndex]
esacc.df<-read.table(text=esaccLines,header=FALSE)
names(esacc.df)<-c("trialnum","blocknum","eventType","eye","startTime","time","v6",
                            "startX","startY","X","Y","v11","v12")
esacc.df$pupilDim<-"na"

#Saccades
ssacc.df$X<-esacc.df$startX
ssacc.df$Y<-esacc.df$startY
ssacc.df$pupilDim<-"na"
esacc.df<-esacc.df[c("trialnum","blocknum","eventType","eye","time","X","Y","pupilDim")]
sacc<-rbind(ssacc.df,esacc.df)

#Start Fixations
sfixLinesIndex<-which(grepl("SFIX", fileLines.tn))
```

```
sfixLines<-fileLines.tn[sfixLinesIndex]

sfix.df<-read.table(text=sfixLines,header=FALSE)

names(sfix.df)<-c("trialnum","blocknum","eventType","eye","time")

sfix.df$X<-"na"

sfix.df$Y<-"na"

sfix.df$pupilDim<-"na"


#End Fixations

efixLinesIndex<-which(grepl("EFIX", fileLines.tn))

efixLines<-fileLines.tn[efixLinesIndex]

efix.df<-read.table(text=efixLines,header=FALSE)

names(efix.df)<-c("trialnum","blocknum","eventType","eye","startTime","time","duration",

                                       "X","Y","pupilDim")

efix.df<-efix.df[c("trialnum","blocknum","eventType","eye","time","X","Y","pupilDim")]


#All events

if (length(trackLosses) > 0) {

  eyePos<-rbind(sacc,sfix.df,efix.df,samples.df,trackLosses.df)

} else {

  eyePos<-rbind(sacc,sfix.df,efix.df,samples.df)
```

```
}

eyePos<-eyePos[with(eyePos, order(time)), ]

eyePos$eventType<-as.character(eyePos$eventType)

eyePos$eye<-as.character(eyePos$eye)

eyePos$time<-as.numeric(eyePos$time)

eyePos$X<-as.numeric(eyePos$X)

eyePos$Y<-as.numeric(eyePos$Y)

eyePos$pupilDim<-as.numeric(eyePos$pupilDim)


#Determine co-ordinates of start fixation and pupil diameter for saccades and
   start fixations

sfixIndex<-which(eyePos$eventType=="SFIX")

ssaccIndex<-which(eyePos$eventType=="SSACC")

esaccIndex<-which(eyePos$eventType=="ESACC")

eyePos$X[sfixIndex]<-eyePos$X[sfixIndex+1]

eyePos$Y[sfixIndex]<-eyePos$Y[sfixIndex+1]

eyePos$pupilDim[sfixIndex]<-eyePos$pupilDim[sfixIndex+1]

eyePos$pupilDim[ssaccIndex]<-eyePos$pupilDim[ssaccIndex+1]

eyePos$pupilDim[esaccIndex]<-eyePos$pupilDim[esaccIndex+1]
```

```
#Add userid
user<-as.numeric(sub("exp.*", "", fileName))
eyePos$userid<-user

#For every event, there is a sample at the same timestamp, remove those samples
eventTimes<-eyePos[-which(eyePos$eventType=="SAMPLES" | eyePos$eventType=="TRACKLOSS"),]$time
index<-which(eyePos$time %in% eventTimes & eyePos$eventType=="SAMPLES")
eyePos<-eyePos[-index,]

#Remove trackloss samples
eyePos<-eyePos[-which(eyePos$eventType=="TRACKLOSS"),]

#For binocular samples, keep the eye with the most samples in the dataset
nR<-nrow(subset(eyePos,eyePos$eye=="R"))
nL<-nrow(subset(eyePos,eyePos$eye=="L"))

if (nR > 0 & nL > 0) {
  dupls<-which(duplicated(eyePos$time))
```

```
  times<-eyePos[dupls,]$time

  eyes<-unique(eyePos[c(dupls,dupls-1),]$eye)

  if (length(eyes)>1) {

    if (nR > nL) {

      eyePos<-eyePos[-which(eyePos$time %in% times & eyePos$eye=="L"),]

    } else {

      eyePos<-eyePos[-which(eyePos$time %in% times & eyePos$eye=="R"),]

    }

  }

}


#Add slides

msgLinesIndex<-which(grepl("MSG", fileLines.tn))

msgLines<-fileLines.tn[msgLinesIndex]

msgLines<-msgLines[1:(length(msgLines)-1)]

msgLines.df<-read.table(text=msgLines,header=FALSE,fill=TRUE)

msgLines.df<-msgLines.df[,c(4,5)]

names(msgLines.df)<-c("time","slide")
```

```
#The time from TRIAL OK to FIX1 follows the reward (sadly don't have the eye
   data for during the reward)
msgLines.df<-droplevels(subset(msgLines.df,msgLines.df$slide!="TRIALID"))
msgLines.df$slide<-ifelse(msgLines.df$slide=="TRIAL","POSTREWARD",as.character(msgLines.df$

#Keep meaningful slides
keepIndex<-which(msgLines.df$slide=="FIX1" |
                 msgLines.df$slide=="CUE" |
                 msgLines.df$slide=="STIMULUS" |
                 msgLines.df$slide=="FIX2" |
                 msgLines.df$slide=="RESPONSE" |
                 msgLines.df$slide=="POSTREWARD" |
                 msgLines.df$slide=="DRIFTCORRECT")
msgLines.df<-msgLines.df[keepIndex,]

#Order by time
msgLines.df$time<-as.numeric(as.character(msgLines.df$time))
msgLines.df<-msgLines.df[with(msgLines.df, order(time)), ]

#Remove duplicated timestamps
```

```
dupls<-which(duplicated(msgLines.df$time))

if (length(dupls) > 0) {

  msgLines.df<-msgLines.df[-dupls,]

}


eyePos$slide<-unlist(lapply(eyePos$time, function(x) {

  diff<-x-msgLines.df$time

  index<-which(diff==min(diff[diff>=0]))

  if (length(index)>0) msgLines.df$slide[index]

  else "PREFIX1"

}))


eyePos$slideStart<-unlist(lapply(eyePos$time, function(x) {

  diff<-x-msgLines.df$time

  index<-which(diff==min(diff[diff>=0]))

  if (length(index)>0) msgLines.df$time[index]

  else eyePos$time[1]

}))


#Adjust x and y for center at (0,0)
```

```
  eyePos$X<-eyePos$X-1024/2
  eyePos$Y<-768/2-eyePos$Y


  #Write the data frame as a .csv
  fn_out<-paste(dirPar,as.character(user),"_ASCparsed.csv",sep="")
  write.csv(eyePos,file=fn_out,row.names=FALSE)
}
```

Eyelink II Data Visualization

Although this function was not used in the analyses presented in the body of the thesis, I have included it here as a unique approach for visualizing eye movement data by trial, type and condition. It was used to validate the output of the parser function above to ensure the data made sense and was consistent.

```
## ================================================================================
## Eyelink II Eye Data Visualization
## By Christie Haskell, 28-07-2015 (v.1)
## ================================================================================


#Required pacakges
```

```
library(ggplot2)

library(grid)

library(gWidgets)

library(gWidgetstcltk)


#Inputs:

#dfori: data frame of beavhaioural data

#dfeye: data frame of eye data


#Outputs

#The GUI and the plot


eyeVisInt<-function(dfori,dfeye) {


  #Modified from gaborPatch in the grt package

  gaborPatch2 <- function (sf, theta = 0, rad = (theta * pi)/180, pc = 1, sigma

      = 1/6,

                           psi = 0, grating = c("cosine", "sine"), npoints = 100,

                               trim = 0,

                           trim.col = 0.5, ...) {
```

```
if (length(npoints) == 1)

  npoints <- rep(npoints, 2)

if (length(sigma) == 1)

  sigma <- rep(sigma, 2)

X <- ((1:npoints[1L])/npoints[1L]) - 0.5

Xm <- matrix(rep(X, npoints[2L]), npoints[2L])

Ym <- t(Xm)

Xt <- Xm * cos(rad) + Ym * sin(rad)

Yt <- -Xm * sin(rad) + Ym * cos(rad)

grating <- match.arg(grating)

if (grating == "cosine") {

  wave <- pc * cos(2 * pi * Xt * sf + psi)

}

else {

  wave <- pc * sin(2 * pi * Xt * sf + psi)

}

gauss <- exp(-0.5 * ((Xt/sigma[1L])^2 + (Yt/sigma[2L])^2))

gabor <- wave * gauss

gabor[gauss < trim] <- (trim.col * 2 - 1)
```

```
  return(gabor)
}

#GUI handler function
p<-function(...) {

  #Modified by the GUI
  user<-as.numeric(svalue(user))
  rew<-svalue(rew)
  cueing<-svalue(cueing)

  if (rew=="None") {
    rewC<-"none"
  } else if (rew=="Fine") {
    rewC<-"high"
  } else if (rew=="Coarse") {
    rewC<-"low"
  }

  if (cueing=="None") {
```

```
  cueingC<-"neutral"

} else if (cueing=="Valid") {

  cueingC<-"true"

} else if (cueing=="Invalid") {

  cueingC<-"false"

}


#List of all trials that meet the conditions set on the GUI

dplot<-subset(dfeye,dfeye$userid==user & dfeye$reward==rewC &

    dfeye$validCue==cueingC)

trials<-unique(dplot$trialnum)


#Trial selected in the GUI

trialIndex<-as.numeric(svalue(trl))

trial<-trials[trialIndex]


dplot<-subset(dplot,dplot$trialnum==trial)

block=unique(dplot$blocknum)


#Which slides to display
```

```
if (svalue(slde)=="Fixation 1") {

  dplot<-subset(dplot,dplot$slide=="FIX1")

}

if (svalue(slde)=="Fixation 2") {

  dplot<-subset(dplot,dplot$slide=="FIX2")

}

if (svalue(slde)=="Stimulus") {

  dplot<-subset(dplot,dplot$slide=="STIMULUS")

}

if (cueing!="None") {

  if (svalue(slde)=="Cue") {

    dplot<-subset(dplot,dplot$slide=="CUE")

  }

}

if (svalue(slde)=="Response") {

  dplot<-subset(dplot,dplot$slide=="RESPONSE")

}


#What was the stimulus position?
```

```
stimPosX<-dfori[which(dfori$userid==user & dfori$blocknum==block &
    dfori$trialnum==trial),]$stimPosXpix
stimPosY<-dfori[which(dfori$userid==user & dfori$blocknum==block &
    dfori$trialnum==trial),]$stimPosYpix

#what was the stimlus orientation?
stimOri<-dfori[which(dfori$userid==user & dfori$blocknum==block &
    dfori$trialnum==trial),]$orient

#What did participants responsd?
respOri<-dfori[which(dfori$userid==user & dfori$blocknum==block &
    dfori$trialnum==trial),]$judgori*pi/180
df.resp<-data.frame("x"=c(stimPosX+40*cos(respOri),stimPosX-40*cos(respOri)),
                           "y"=c(stimPosY+40*sin(respOri),stimPosY-40*sin(respOri)))

#eventType colours and sizes
cols<-c("Start Saccade"="red","End Saccade"="red2","Start
    Fixation"="yellow","End Fixation"="yellow2")
shapes<-c("Start Saccade"=17,"End Saccade"=15,"Start Fixation"=17,"End
    Fixation"=15)
```

```
#Order of legend
dplot$eventType <- factor(dplot$eventType, levels = c("Start Saccade","End
   Saccade","Start Fixation","End Fixation"))

#Stimulus
gabPat<-gaborPatch2(4,theta = stimOri,pc = 0.6525,npoints =
   500,trim=0,trim.col=NA,grating="sine")
gabAdj<-gabPat-min(gabPat)
gabAdj2<-ifelse(gabAdj<=1,gabAdj,1)
gabIm<-as.raster(gabAdj2)
g<-rasterGrob(gabIm,interpolate=TRUE)

#Theme settings
ptheme<-theme(panel.grid.major = element_blank(),
             panel.grid.minor = element_blank(),
             axis.line=element_blank(),
             axis.text.x=element_blank(),
             axis.text.y=element_blank(),
             axis.ticks=element_blank(),
```

```
              axis.title.x=element_blank(),
              axis.title.y=element_blank(),
              panel.background = element_rect(fill
                 =rgb(-min(gabPat),-min(gabPat),-min(gabPat))),
              legend.position=c(0,1),
              legend.justification=c(0,1),
              legend.background =
                 element_rect(fill=rgb(-min(gabPat),-min(gabPat),-min(gabPat))),
              legend.key =
                 element_rect(fill=rgb(-min(gabPat),-min(gabPat),-min(gabPat))))

#Legend settings
pguide<-guides(colour = guide_legend(override.aes = list(size=4)))

#Fixation and trial number
fix<-geom_point(aes(x=0,y=0),colour="white",size=4.55)
trialNum<-annotate("text", x = 450, y = 375, label = paste("Trial Number:
   ",unique(as.character(dplot$trialnum)),sep=""))

#Cue
```

```
if (cueing!="None") {

  #What was the cue position?

  cuePosX<-as.numeric(as.character(dfori[which(dfori$userid==user &

      dfori$blocknum==block & dfori$trialnum==trial),]$cuePosXpix))

  cuePosY<-as.numeric(as.character(dfori[which(dfori$userid==user &

      dfori$blocknum==block & dfori$trialnum==trial),]$cuePosYpix))

  df.cue<-data.frame("x"=cuePosX,"y"=cuePosY)


  pcue<-geom_rect(data=df.cue,aes(NULL,NULL,xmin=x-50,xmax=x+50,ymin=y-50,ymax=y+50),

                              colour="white",alpha=0,size=1.5)

}


#What event types to plot?

if (svalue(sacc)=="TRUE") {

  dplot<-subset(dplot,dplot$eventType=="Start Saccade" |

      dplot$eventType=="End Saccade")

}


if (svalue(fixate)=="TRUE") {
```

```
  dplot<-subset(dplot,dplot$eventType=="Start Fixation" |
      dplot$eventType=="End Fixation" | dplot$eventType=="Fixation Update")
}

#Stimulus and response
pstim<-annotation_custom(grob =
    g,xmin=stimPosX-40,xmax=stimPosX+40,ymin=stimPosY-40,ymax=stimPosY+40)
presp<-geom_line(data=df.resp,aes(x=x,y=y),colour="black",size=1)

#Eye data points
points<-geom_point(aes(colour=eventType,shape=eventType),size=6,alpha=0.5)

#Eye data path
plines<-geom_line()

#The base plot
p<-ggplot(dplot,aes(x=X,y=Y))+ylim(c(-768/2,768/2))+xlim(c(-1024/2,1024/2))+
  scale_colour_manual(name="Event Type",values = cols)+
  scale_shape_manual(name="Event Type",values = shapes)
```

```
#Building the plot based on options selcted on the GUI

if (svalue(slde)=="Fixation 1") {

  plot<-p+ptheme+fix+pguide

} else if (svalue(slde)=="Fixation 2") {

  plot<-p+ptheme+fix+pguide

} else if (svalue(slde)=="Stimulus") {

  plot<-p+pstim+ptheme+fix+pguide

} else if (svalue(slde)=="Cue") {

  plot<-p+pcue+ptheme+fix+pguide

} else if (svalue(slde)=="Response") {

  plot<-p+presp+ptheme+fix+pguide

} else if (svalue(slde)=="All") {

  if (cueing!="None") {

    plot<-p+pcue+pstim+presp+ptheme+fix+pguide

  } else {

    plot<-p+pstim+presp+ptheme+fix+pguide

  }

}


if (svalue(pth)=="TRUE") {
```

```
    plot<-plot+plines
  }

  if (svalue(pts)=="FALSE") {
    plot<-plot+points
  } else if (svalue(pts)=="TRUE") {
    plot<-plot
  }

  #Print the plot
  print(plot+trialNum)
}

#Set up of the GUI
win_ctrls <- gwindow("Plot controls")
tbl = glayout(container=win_ctrls)
tbl[1,1]<-"Group:"
tbl[1,2]<- (grp<-gcombobox(unique(dfeye$group), selected = 1,
    width=70,editable=FALSE, container=tbl))
tbl[2,1]<-"Participant: "
```

```
tbl[2,2]<- (user<-gcombobox(character(0), editable=FALSE, width=70,
   container=tbl, handler=p))
tbl[3,1]<-"Reward: "
tbl[3,2]<- (rew<-gcombobox(character(0), editable=FALSE, width=70,
   container=tbl, handler=p))
tbl[4,1]<-"Cueing: "
tbl[4,2]<- (cueing<-gcombobox(c("Invalid","None","Valid"), selected = 1,
   width=70, editable=FALSE, container=tbl, handler=p))
tbl[5,1]<- (sacc<-gcheckbox("Saccade Only", checked = FALSE,
   container=tbl,handler=p))
tbl[5,2]<- (fixate<-gcheckbox("Fixation Only", checked = FALSE,
   container=tbl,handler=p))
tbl[6,1]<- (pth<-gcheckbox("Draw Path", checked = FALSE,
   container=tbl,handler=p))
tbl[6,2]<- (pts<-gcheckbox("Remove Points", checked = FALSE,
   container=tbl,handler=p))
tbl[7,1]<-"Slide: "
tbl[7,2]<-(slde<-gradio(c("All","Fixation 1","Cue","Stimulus","Fixation
   2","Response"), selected=1, container=tbl,handler=p))
tbl[8,1]<-"Trials"
```

```
tbl[8,2]<- (prev<-gbutton(text = "Prev", border=TRUE, container = tbl))

tbl[8,3]<- (trl<-gedit(text = "1", width = 5, handler = p, container = tbl))

tbl[8,4]<- (nex<-gbutton(text = "Next", border=TRUE, container = tbl))


#HT34-rA3 <- pass, birttlab artsresearch


#Fill the userid and reward combo boxes

addHandlerChanged(grp, handler=function(...) {

  users <- unique(subset(dfeye,dfeye$group==svalue(grp))$userid)

  user[] <- users

  svalue(user)<-users[1]

  if (svalue(grp)=="NF") {

    rew[]<-c("None","Fine")

    svalue(rew)<-"None"

  } else if (svalue(grp)=="HF") {

    rew[]<-c("Fine","Coarse")

    svalue(rew)<-"Fine"

  } else if (svalue(grp)=="LF")

    rew[]>=c("Coarse","Fine")

  svalue(rew)<-"Coarse"
```

```
  })

  #Go back one trial
  addHandlerChanged(prev, handler=function(...) {
    current<-as.numeric(svalue(trl))
    if (current > 1) {
      newTrl<-current - 1
      svalue(trl)<-newTrl
    }
  })

  #Go forward one trial
  addHandlerChanged(nex, handler=function(...) {
    current<-as.numeric(svalue(trl))
    newTrl<-current + 1
    svalue(trl)<-newTrl
  })
}
```