

Enhancing mechanisms of spatial learning in real and simulated environments

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Abstract

Efficient search benefits from persistent exposure to the statistical liklihoods that underpin object locations, such that time and energy expenditure tends be minimal. Inspections are made towards areas where objects are most likely to appear or have previously produced successful results. Experimentally, this phenomena has been named the 'probability cueing effect', and has predominantly been studied using visual search paradigms. In this context, participants bias their search towards locations where a target frequently appears, but they do not express any conscious awareness of doing so. However, in real-world tasks, it is much harder for spatial inferences to be made, with additional factors to be considered, such as consistency in where search is inititated. When the cue is learnt, it is instead consciously acknowledged.

The research within this Thesis investigated search in an additional context: virtual, representational space. Probability cueing was successful but only when the environment was of minimal immersion. Parallel to visual search, participants did not express an awareness of the cue suggesting that physical movement is important for conscious awareness of learning. The transfer of probability cueing across virtual to real space was also examined, although an effect was not established. This finding has important applied implications, when considering that virtual environments are used throughout many industries as training tools.

To conclude, three experiments investigated the underlying neural system that may support probability cueing, specifically the right parietal cortex. Much research has shown that this area plays a key role in allocating spatial attention across hemifields, but its input for probability cueing has not yet been investigated. These experiments used transcranial anodal (excitatory) and cathodal (inhibitory) stimulation to moduate this brain area. In a visual, 2D task and a 3D virtual environment task, search efficiency was modulated, with both stimulation types improving general search profiles. In a real-world task, search efficiency was again modulated, as well as probability cueing with stimulation interacting with the high-probability hemispace.

Together these studies provide a comprehensive understanding of probability cueing under various environmental search constraints, and the role of the right parietal cortex in the guidance of this search strategy.

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Table of contents

1 INTRODUCTION 1

1.1 Probability cueing 1

1.1.1 Visual search and probability cueing 2

1.1.2 Functional basis of probability cueing 6

1.1.3 Probability cueing in large-scale space 11

1.1.4 Neuronal basis of probability cueing 19

1.1.4.1 Hemispatial neglect 20

1.1.4.2 Hemispatial neglect and probability cueing 23

1.2 Manipulations of spatial learning 27

1.2.2 Transcranial direct current stimulation (tDCS) 28

1.2.2.1 Mechanisms of action 28

1.2.2.2 Manipulations of search behaviour and spatial attention 31

1.3 Thesis overview 38

2 METHODOLOGIES FOR EXAMINING SPATIAL LEARNING 40

2.1 Virtual environments 40

2.1.1 Considerations 42

2.1.1.1 Technical factors 42

2.1.1.2 Participant considerations 45

2.1.1.3 General advantages and disadvantages 47

2.1.2 Summary 49

2.1.3 VEs in the current research 50

2.1.3.1 Array creation 50

2.1.3.2 Start position and trial probability 52

2.1.3.3 VE visual appearance 66

2.1.3.4 Deriving spatial learning measures 68

2.1.3.5 Monitoring simulator sickness 60

2.2 tDCS 61
2.2.1 Considerations 63
2.2.1.1 Methodological considerations 63
2.2.1.2 tDCS parameters 65
2.2.1.3 Participant considerations 67
2.2.1.4 General advantages and disadvantages 69
2.2.2 Summary 70

2.3 Measuring spatial learning 71

2.4 VEs, tDCS and spatial learning 74

3 PROBABILITY CUEING IN VIRTUAL AND LABORATORY SPACE 76

3.1 Introduction 76

3.2 Experiment 1A: Probability cueing in virtual space 81
3.2.1 Method 84
3.2.1.1 Participants 84
3.2.1.2 Materials 85
3.2.1.3 Procedure 87
3.2.2 Results 88
3.2.2.1 Behavioural results 90
3.2.2.2 Individual differences 98
3.2.3 Discussion 104

3.3 Experiment 1B: Examining probability cueing over time 109
3.3.1 Method 110
3.3.1.1 Participants 110
3.3.1.2 Materials 110
3.3.1.3 Procedure 111
3.3.2 Results 111
3.3.2.1 Behavioural results 111

3.3.2.2 Individual differences 116
3.3.3 Discussion 120

3.4 Experiment 2: Probability cueing in immersive space 124
3.4.1 Method 125
3.4.1.1 Participants 125
3.4.1.2 Materials 126
3.4.1.3 Procedure 128
3.4.2 Results 129
3.4.2.1 Behavioural results 129
3.4.2.2 Individual differences 130
3.4.3 Discussion 137

3.5 Experiment 3: Probability cueing in full-body search 141
3.5.1 Method 146
3.5.1.1 Participants 146
3.5.1.2 Materials 147
3.5.1.3 Procedure 153
3.5.2 Results 155
3.5.2.1 Behavioural results 157
3.5.2.2 Individual differences 158
3.5.3 Discussion 163

3.6 General discussion 166

4 TRANSFER OF PROBABILITY CUEING 177

4.1 Introduction 177

4.2 Experiment 4: Transfer of probability cueing 183

4.3 Method 185
4.4.1 Participants 185
4.4.2 Materials 186

4.4.3 Procedure 189

4.4 Results 192

4.4.1 Behavioural results 193

4.4.2 Individual differences 201

4.5 Discussion 212

5 THE NEURAL BASIS OF PROBABILITY CUEING 221

5.1 Introduction 221

5.2 tDCS in the current research 228

5.3 Experiment 5: RPC tDCS and visual search 233

5.3.1 Method 236

5.3.1.1 Participants 236

5.3.1.2 Materials 237

5.3.1.3 tDCS protocol 238

5.3.1.4 Procedure 239

5.3.2 Results 241

5.3.2.1 Behavioural results 245

5.3.2.2 Individual differences 251

5.3.3 Discussion 256

5.4 Experiment 6: RPC tDCS and virtual search 262

5.4.1 Method 267

5.4.1.1 Participants 267

5.4.1.2 Materials 267

5.4.1.3 tDCS protocol 269

5.4.1.4 Procedure 269

5.4.2 Results 270

5.4.2.1 Behavioural results 272

5.4.2.2 Individual differences 278

5.4.3 Discussion 287

5.5 Experiment 7: RPC tDCS and full-body search 292

5.5.1 Method 295

5.5.1.1 Participants 295

5.5.1.2 Materials 296

5.5.1.3 tDCS protocol 301

5.5.1.4 Procedure 301

5.5.2 Results 303

5.5.2.1 Behavioural results 303

5.5.2.2 Individual differences 313

5.5.3 Discussion 319

5.6 General discussion 325

6 OVERVIEW AND GENERAL CONCLUSION 334

6.1 Experiments 1 and 2: Probability cueing in virtual space 335

6.2 Experiment 3: Probability cueing in large-scale space 344

6.3 Experiment 4: Transfer of probability cueing 347

6.4 Experiments 5, 6 and 7: A role for the RPC in probability cueing 354

6.6 Overall evaluation and conclusions 367

References 372

Appendix 1: tDCS Safety Questionnaire 403

Appendix 2: tDCS Screening Questionnaire 404

Appendix 3: EHI Questionnaire and Scoring 405

Appendix 4: Experiment 5, Pairwise comparisons results I **407**

Appendix 5: Experiment 5, Pairwise comparisons results II **408**

List of Figures

Figure 1.1 **A:** Kinsbourne (1987). *Left*: In the intact brain, inhibition keeps the two hemispheres in equilibrium. *Right*: When the right hemisphere is lesioned, it becomes hyperactive and the left hemisphere becomes more inhibited, causing the effects of hemispatial neglect. **B:** Heilman and colleagues (1979; 1980): *Left*: In the intact brain, the right hemisphere controls left and right hemifields whereas the left hemisphere controls the right only. *Right*: When the right hemisphere is lesioned, the left hemifield is neglected and the left hemisphere controls the right hemifield only.....22

Figure 1.2 tDCS equipment. From bottom left to the top: Washable pen, measuring tape, rubber electrodes, electrode cables, conductive gel, sponge electrode pads, tDCS stimulator, tDCS parameter programmer, power cables (grey and black), tight fitting cap. 29

Figure 2.1: **A**: Six arrays created in Microsoft Excel using a basic rule: each search location appeared in one row and one column only. **B**: Arrays randomly combined into 4 quadrants to create a larger 6x6 grid with 12 search locations overall. This was conducted 20 times. 52

Figure 2.2 VE viewed from the start position. *Left:* VE used in Experiments 1, 4 and 6; *right:* VE used in Experiment 2. 57

Figure 2.3 MazeAnalyzer software showing a region file, with all data from 30 trials and the regions of interest (purple boxes) superimposed on the file. 59

Figure 3.1 VE visual appearance for Experiments 1A and 1B. 85

Figure 3.2 Reduction in median search time on cued trials compared to uncued trials (main effect of trial type) and a reduction in overall search time across the two blocks (main effect of block). Error bars represent +/-1 standard error of the mean, $*p < 0.05$.....91

Figure 3.3 Percentage of first visits were significantly above 50% chance in Block 1 and 2. Error bars represent +/-1 standard error of the mean, $*p < 0.05$. 93

Figure 3.4 Density was significantly above 50% chance for Block 1 and Block 2. Error bars represent +/-1 standard error of the mean, *p < 0.05.....95

Figure 3.5 A significant reduction in the number of visits to items on cued trials compared to uncued trials. Error bars represent +/-1 standard error of the mean, *$p < 0.05$.....97

Figure 3.6 Density was significant above 50% chance across all epochs. Error bars represent +/-1 standard error of the mean, *$p < 0.05$. 114

Figure 3.7 Experiment 2 set-up. *Left*: Schematic diagram of the environment. Cylinders represent coloured projectors. *Right*: Participants view of the environment. 127

Figure 3.8 Plan view of the laboratory space. Dashed lines were not visible. Before activation, the target appeared visually the same as the other search items. 148

Figure 3.9 The laboratory space with a search array. The green tape marked the south of the space and the red tape marked the start position. 150

Figure 3.10 Tobii eyetracking glasses. Image not under copyright restrictions: https://commons.wikimedia.org/wiki/File:Tobii_Glasses_2_Eye_Tracker_Wearable_System_Tobii_I.jpg. 152

Figure 4.1 Block 2 search time was quicker than Block 1 in the training phase. Search time to previous uncued trials was quicker than previously cued trials in the first 10 trials. Data displayed for the testing phase are to previously cued and previously uncued trials. Error bars represent +/-1 standard error of the mean, *$p < 0.05$. 195

Figure 4.2 Density was significantly above *50% chance* for the training blocks and significantly increased between them. Data displayed for the testing phase is to the previously cued side. Error bars represent +/-1 standard error of the mean, *$p < 0.05$. 198

Figure 4.3 More visits were made on previously cued trials than cued trials in the first 10 trials. Data displayed for the testing phase are to previously cued and previously uncued trials. Error bars represent +/-1 standard error of the mean, *$p < 0.05$. 200

Figure 5.1 RPC/LPC tDCS set-up. Electrodes were attached using a rubber cap, but for illustrative purposes they are shown with rubber straps.230

Figure 5.2 ARPC is portrayed by red; CRPC is portrayed by green. **A:** General predictions: ARPC will enhance probability cueing; CRPC will slow probability cueing. Arrows are spread to indicate a global change to RT on cued trials. **B:** Specific predictions: ARPC will enhance search when the cue is on the left and CRPC will slow search when the cue is on the left.....234

Figure 5.3 Histogram illustrating the raw data in Experiment 5.....242

Figure 5.4 Histogram illustrating the log transformed data in Experiment 5. 245

Figure 5.5 Significant trial type x block interaction. As the trials progressed, cued trials incurred speedier responses than uncued trials. Error bars represent +/-1 standard error of the mean. 248

Figure 5.6 RT for cued, uncued and all trials. ARPC were significantly faster at completing the task than CRPC. Error bars represent +/-1 standard error of the mean, $*p < 0.05$. 249

Figure 5.7 Significant group x trial type interaction effect. CRPC conducted significantly more visits on uncued trials than cued trials; Sham significantly increased their visits on cued trials than uncued trials, and conducted more visits on cued trials compared to ARPC and CRPC. Error bars represent +/-1 standard error of the mean. 277

Figure 5.8 Participant interacting with the apparatus. 297

Figure 5.9 Experiment 7 arrays. Red indicates start positions; green indicates legal locations permitted during the array designs; yellow indicates potential target locations; white indicates illegal locations. 300

Figure 5.10 Significant trial type x block interaction effect. More visits were made on cued trials in Block 1 than Block 2, but uncued trials encompassed more visits in Block 2 than Block 1. In Block 2, there were less visits on cued than uncued trials. Error bars represent +/-1 standard error of the mean. 310

List of Tables

Table 1.1 Differences between laboratory visual search tasks, and real-world search. 11

Table 1.2 Details of the various factors manipulated during each experimental design tested in a large-scale probability cueing task, by Smith et al. 2010.....16

Table 2.1 Randomising trial procedure demonstrating how target locations inform the cued and uncued sides of the display. Start positions are represented in the MazeSuite diagrams as grey circles; target locations are numbered; lights are represented by yellow circle. Dashed lines represent the invisible quadrant. 54

Table 3.1 Examples of phrases and key words coded as implicit or explicit knowledge of the target's location 99

Table 3.2 Experiment 1A - Post-Experiment Questions. Participants identified the target's location when given a force-choice probe. *$p < 0.05$, **$p \leq 0.001$.....100

Table 3.3 Experiment 1A – Pearson's Product-Moment Correlations (r and α) and a Point-Biserial Correlation (r_{pb} and α) for the cueing effect and questionnaire measures, *$p < 0.05$, **$p \leq 0.001$. 103

Table 3.4 Means and standard deviations for search time (s) overall and for each trial type, for all epochs. 112

Table 3.5 Means and standard deviations for the number of visits overall and for each trial type, for all epochs. 115

Table 3.6 Experiment 1B - Post-Experiment Questions. Behaviourally probability cueing was attenuated, but participants still expressed some knowledge of the target's location when questioned. *$p < 0.05$, **$p \leq 0.001$.....117

Table 3.7 Experiment 1B - Pearson's Correlation values (r) and alpha values (α) from product moment correlations and a Point-Biserial Correlation (r_{pb}) for the cueing effect and questionnaire measures. N= 20 for all analyses; *$p < 0.05$, **$p \leq 0.001$. 119

Table 3.8 Experiment 2 - Post-Experiment Questions. Behaviourally probability cueing was attenuated, but participants still expressed some knowledge of the target's location when questioned. *$p < 0.05$, **$p \leq 0.001$.....131

Table 3.9 Mean ratings of the SSQ for each sub-score at the beginning of the experiment (time-point 1), after the practice trials (time-point 2) and at

the end of the experiment (time-point 3). Symptoms that form the sub-scores are detailed. 133

Table 3.10 Experiment 2 - Pearson's Product-Moment Correlations (r and α) and a Point-Biserial Correlation (r_{pb} and α) for the cueing effect and questionnaire measures, *$p < 0.05$, **$p \leq 0.001$. 135

Table 3.11 Experiment 3 - Post-Experiment Questions. Explicit and implicit knowledge was absent. **$p < 0.001$ 160

Table 3.12 Experiment 3 - Pearson's Product-Moment Correlations (r and α) and a Point-Biserial Correlation (r_{pb} and α) for the cueing effect and questionnaire measures, *$p < 0.05$, **$p \leq 0.001$. 162

Table 4.1 Experiment 4 – Post-Experiment Questions. Participants reported minimal knowledge of transfer, in line with behavioural results. *$p < 0.05$, **$p \leq 0.001$. 206

Table 4.2 Experiment 4 - Pearson's Product-Moment Correlations (r and α) and a Point-Biserial Correlation (r_{pb} and α) for the cueing effect and questionnaire measures, *$p < 0.05$, **$p \leq 0.001$ 210

Table 5.1 Means and standard deviations for RT (ms) per block, per trial type, and overall.....246

Table 5.2 Experiment 5 - Post-Experiment Questions. Many participants accurately identified the target's location when given a force-choice probe, suggesting that learning was below conscious level. ** $p \leq 0.001$. 253

Table 5.3 Experiment 5 - Pearson's Product-Moment Correlations (r and α) and a Point-Biserial Correlation (r_{pb} and α) for the cueing effect and questionnaire measures, *$p < 0.05$ 255

Table 5.4 Experiment 6 - Post-Experiment Questions. Most participants guessed the cued side when presented with a forced-choice probe. **$p \leq 0.001$ *$p < 0.05$ 281

Table 5.5 Experiment 6 - Pearson's Product-Moment Correlations (r and α) and a Point-Biserial Correlation (r_{pb} and α) for the cueing effect and questionnaire measures, *$p < 0.05$, **$p \leq 0.001$ 284

Table 5.6 Experiment 7 - Post-Experiment Questions. All participants guessed the cued side correctly when presented with a forced-choice probe ** $p \leq 0.001$ 315

Table 5.7 Experiment 7 - - Pearson's Product-Moment Correlations (r and α) and a Point-Biserial Correlation (r_{pb} and α) for the cueing effect and questionnaire measures, *$p < 0.05$, **$p \leq 0.001$ 318

Table 6.1 Effect sizes for Experiments 1A, 1B and 2 (*$p < 0.05$). 339

Table 6.2 Effect sizes for Experiment 3 (*$p < 0.05$) 345

Table 6.3 Effect sizes in Experiment 4 (*p < 0.05).. 350

Table 6.4 Trial type and group effect sizes for Experiments 5-7 (*$p < 0.05$) 358

Table 6.5 Cued side and group effect sizes for Experiment 5-7 (*$p <$0.05). 363

1 Introduction

1.1 Probability cueing

The world is extremely complex, containing a large amount of detail, motion, colour and shape which all come together to create a visual scene. The human brain is constantly flooded with this information. Despite this, relevant visual information is extracted by the human brain, meaning that successful search for objects of interest can be undertaken (Walthew & Gilchrist, 2006).

Although our environments are complex, objects are rarely positioned in random or unpredictable places (Biederman, 1972; Walthew & Gilchrist, 2006). Instead, objects tend to be in locations that are associated or related to a particular context (Biederman, 1972) – for example, your toothbrush is most likely to be found in a bathroom rather than outside in the garden. Even objects that can move are bound by statistics and appear regularly in the same context (Brockmole & Henderson, 2006); for example, a car is most likely to be on the road or in a garage. Overall, these natural statistical relations help create cohesion of objects which overtime can become meaningful, predictive and familiar through learning (Jones & Kaschak, 2012). In turn, learning the spatial locations of objects helps us to optimally and efficiently search. Furthermore, we do not need any form of explicit instruction or any intention to learn these statistical properties (Perruchet & Pacton, 2006); it seems as though statistical learning is an automatic mechanism which starts at an early age (Kirkham, Slemmer, & Johnson, 2002). Animals are also able to use strategies to effectively learn their

environments to guide their search. For example, a bird may use prior knowledge of its catch rate in one location to anticipate whether the observed catch rate in a new location is predictable of successful foraging (Clark & Mangel, 1984). This implicit hypothesis testing helps animals and humans to optimally search an environment by saving time, energy and resources. In the psychology literature this learning process is termed the 'probability cueing effect' and is defined by a search bias towards regions of space where objects of interest are repeatedly most likely to occur (Geng & Behrmann, 2002; Jiang & Swallow, 2013).

The purpose of this Chapter is to review the literature related to human spatial learning across visual and large-scale search modelled on real-world foraging behaviour. The focus will be on studies examining probability cueing. This is then followed by an overview of the neurological basis of efficient search behaviour, and how this behaviour has been examined from a neuropsychology perspective. Following this, examples of how search behaviour and spatial attention have been manipulated using transcranial direct current stimulation (tDCS) techniques will be discussed, in line with theories of spatial attention. Finally, a Thesis overview will conclude this chapter.

1.1.1 Visual search and probability cueing

Visually scanning and searching an environment to locate an object is a fundamental human survival behaviour. There have been thousands of publications examining visual search and its various manifestations in all different types of contexts and using a variety of methodologies (for reviews see: Oliva & Torralba, 2007; Wolfe,

1994; Wolfe, 1998). For example, a PubMed literature search using the phrase 'visual search', produces just short of 10,500 articles (July, 2017). In the basic visual search paradigm, participants are required to search for a target item amongst other distractor items, and to produce a response (e.g. a button press) when they have found the target (Wolfe, 1994). This task has been used to investigate many cognitive processes including attention, memory, decision-making and rewards (Eckstein, 2011). For the majority of these laboratory-based tasks, the target is placed in a random location on every trial (Oliva & Torralba, 2007) and is equally likely to appear across many possible locations (Walthew & Gilchrist, 2006). In most cases, the target and distractors are isolated from a scene or context (Biederman, 1972; Wolfe, 1994) and instead appear on a blank background. Although it has been argued that visual search is a good model of naturalistic foraging behaviour (Klein & MacInnes, 1999; Wolfe, 1994), it must be remembered that the displays are unlike our natural environment, which is dynamic and rich with statistically-bound objects.

Several studies have attempted to address these issues by examining how humans can detect the presence of statistically manipulated stimuli in a visual array. Of most relevance to this Thesis, research has shown that a target can be detected faster if it is located within a high-probability region of space rather than a low-probability region (e.g. Geng & Behrmann, 2002; Geng & Behrmann, 2005; Jiang, Won, & Swallow, 2014; Walthew & Gilchrist, 2006). This indicates that previously learnt experiences of the predictable relationships between objects and their locations, optimises human search performance. Furthermore, having explicit knowledge or an intention to learn is not necessarily required to guide search towards high probabilistic

locations (Chun & Jiang, 1998; Jiang & Swallow, 2013). This implicit, incidental learning process is known as probability cueing. This learning is unlike other types of attentional biases, in that probability cueing does not necessarily rely purely on repetition priming (Geng & Behrmann, 2005), it can persist over time (Jiang, Swallow, & Rosenbaum, 2012) and it reflects the stability and coding of objects within a dynamic environment (Jiang & Swallow, 2013).

Geng and Behrmann (2002) were the first researchers to report probability cueing. Each participant in their experiment completed two conditions. In the baseline condition, the target was evenly distributed across space, so that it was located 50% of the time on one side and 50% on the other side of the search array. In the uneven condition, however, the target's location was statistically manipulated so that it appeared 80% of the time on one side of the display (cued side) and 20% on the other (uncued side). Participants were not explicitly directed to the cued side of the array; they were simply instructed to search for the target amongst the distractors on each trial. Results suggested that the statistical regularities in the uneven condition improved search efficiency from baseline: reaction time (RT) decreased when the target was located on the cued side of space, in comparison to the uncued side. When questioned, participants did not report any awareness of the probability cue, suggesting that learning occurred below a conscious level. Overall, these results suggest that search was biased towards locations which had previously produced positive outcomes, in turn, increasing efficiency and accuracy of search (Stankevich & Geng, 2014).

Since Geng and Behrmann's (2002) seminal research, further studies have confirmed that humans are able to learn the underlying statistics of a visual array and

bias their search towards a cued region (e.g. Geng & Behrmann, 2005; Jiang & Swallow, 2013; Jones & Kaschak, 2012; Kabata & Matsumoto, 2012; Shaqiri & Anderson, 2012; Stankevich & Geng, 2014; Walthew & Gilchrist, 2006). Furthermore, the effects of probability cueing can persist for long periods of time (Jiang, et al., 2012), and learning of spatial likelihoods occurs early in the trial sequence (Jiang, Swallow, & Rosenbaum, 2013). It has been suggested that probability cueing differs from other forms of attentional cueing, primarily because of the longevity of the effect (Jiang & Swallow, 2013)[1], its ability to transfer to new contexts (Jiang, Swallow, Won, Cistera, & Rosenbaum, 2016) adapt to environments quickly (Jiang & Swallow, 2013) and the understanding that facilitation of this cueing behaviour is independent from endogenous 'reflexive' cueing (Geng & Behrmann, 2005; Jiang et al., 2013). Additionally, it has been demonstrated that the stronger the statistical bias in the visual array (e.g. target appears 70% or 80% on one side of the array and the equivalent percentage on the other) the more likely spatial learning is to bias attention in the same way as monetary reward associations (Stankevich & Geng, 2014). It has also been shown that location is more effective in biasing visual attention than salient, colour cues (Fecteau, Korjoukov, & Roelfsema, 2009). Probability cueing therefore seems to be a form of 'incidental learning' (Jiang & Swallow, 2013).

[1] It has been shown that probability cueing effects can last for up to a week, with participants still biasing their search towards a previously cued side many trials into the experiment (Jiang et al., 2013). In comparison, when participants are exposed to an explicit cue directing them towards a targets location (i.e. an endogenous, experience-driven cue), they can adjust their attentional biases almost immediately after seeing it (~300ms) (Müller & Rabbitt, 1989). There is also a similar re-adaptive effect when a salient cue is repeated across trials (Maljkovic & Nakayama, 1994). This emphasises the potential differences between probability cueing and attentional mechanisms, namely, experience-driven, endogenous cueing, and stimulus-driven exogenous cueing.

1.1.2 Functional basis of probability cueing

An issue still open to debate is the functional basis of probability cueing. Traditionally, probability cueing has been interpreted in terms of statistical learning (Geng & Behrmann, 2002, 2005), which is the long term process of tracking probabilistic information in order to predict where a target is most likely to appear (Geng & Behrmann, 2002, 2005; Goschy, Bakos, Mueller, & Zehetleitner, 2014; Kabata & Matsumoto, 2012; Jones & Kaschak, 2012). The statistical learning effects that operate below conscious level in probability cueing tasks are consistent with learning in visual, auditory, motor and language learning (for a review see Perruchet & Pacton, 2006). However, a number of probability cueing studies may have been confounded by the repetition of the target location over the course of the trial sequence (Goschy et al., 2014). This could induce intertrial repetition priming (Rabbitt, Cumming & Vyas, 1979; Maljkovic & Nakayama, 1996; Walthew & Gilchrist, 2006) - a transient process in which optimal search is produced on the basis of the repetition of the target's location across the trial sequence (Kabata & Matsumoto, 2012). The repetitive nature of a target's location can bias eye movements (Walthew & Gilchrist, 2006) immediately back the previous target location, leading to an enhancement in search and attention.

A collection of experiments by Walthew and Gilchrist (2006) examined the effect of intertrial repetition priming on search performance. In Experiment 3, participants were asked to find a Landolt 'C' facing upwards (the target) amongst seven distractor items, which were of similar appearance but differing orientation. The search array was displayed for 1000ms and participants had to respond to the target using an

eye movement in a saccade-to-target task. The aim of this experiment was to compare whether restricting or repeating a target's location over a trial sequence had differential effects on visual search. Alongside the repeated and non-repeated target conditions, the probability cueing paradigm was used; participants were unaware that the target was twice as likely to appear in one out of the four locations. Results suggested that more correct first saccades were directed to the target when it was in a highly probabilistic location on repeated trials in comparison to unrepeated trials. In these trials, first saccades were instead sporadic and no probability cueing was induced. Furthermore, RT benefited from the repetition of the target's location over the trial series and there was no longer a probability cueing effect if the target's location was not constant across more than four trials. The authors concluded that learning the statistical likelihoods within the search array was a 'by product' of intertrial repetition priming, rather than a causal factor (c.f. Geng & Behrmann, 2005).

Although there have been other converging reports suggesting that probability cueing is absent when repetitions of a target's location is restricted (e.g. Kabata & Matsumoto, 2012), the role of intertrial repetition priming as a primary causal factor has been challenged. Jones and Kaschak (2012) replicated the basic stimuli used in the task by Walthew and Gilchrist (2006) but made some important changes to the overall design of their experiment. The authors claim that the task and the instructions given to participants by Walthew and Gilchrist (2006) may not have been sensitive to the global statistical properties of the search array. Participants were instructed to respond using eye movements only, directed towards *the target*. These instructions assume that target detection requires only local properties of a search array to be processed and sampled

discretely, rather than considering the array as a whole, as this strategy would be irrelevant to completing the task. However, eye tracking studies have suggested that in some cases, participants process global features of a search array before local features (Zangemeister, Sherman, & Stark, 1995). Furthermore it is thought that within probability cueing tasks, attention is weighted towards the cued *region* of space (global feature), rather than individual locations (local feature) across the array (Geng et al., 2013). This has further implications for Walthew and Gilchrist's (2006) design, in that the limited time window (1000ms) that participants had to respond within may have just been enough time to bias search towards the cued side on unrepeated trials, rather than the target specifically. Thus, Jones and Kaschak (2012) claim that the saccade-to-target task and the instructions given to participants may have masked the effects of global features on search performance, in turn, disguising any learning on unrepeated trials.

In their study, Jones and Kaschak (2012) investigated the processing of local and global features in unrepeated trials whilst participants underwent eye tracking. The same unrepeated trial design and stimuli used by Walthew and Gilchrist (2006) was adhered too, however, participants were given an infinite amount of time to complete each trial and were instructed to make a button press (rather than a saccade) to indicate the *side of the display* that the target was located on. First saccade measures indicated that participants looked more towards the cued side of the display, no matter whether the target was on the cued or uncued side. Thus, participants processed the global statistics of the display before the local features and could learn the target's location even when it did not repeat over consecutive trials. These results show how powerful a

simple manipulation to an experimental design can be at altering conclusions drawn from search behaviour and learning effects.

Although both aforementioned studies are discrepant in their results, there have been further studies in which repetitions of a target's location have been minimised and probability cueing effects have been produced (Jiang et al., 2014). In these studies, many search locations (up to 100 in some cases) have been used to avoid natural repetitions of the target to a specific location (Jiang et al., 2014). This is unlike most probability cueing studies where the target and distractors may be fixed to a small number of locations (e.g. Geng & Behrmann, 2002, 2005; Kabata & Matsumoto, 2012). This is exemplified by the Jones and Kaschak (2012) and Walthew and Gilchrist (2006) designs, when both target and distractors could appear only in eight locations across the visual array. Overall this point again highlights that conclusions drawn from visual search tasks may not truly reflect visual search within a natural environment, as objects may be dispersed across a variety of locations, rather than limited.

Another factor to consider is that statistical learning and intertrial repetition priming may not be mutually exclusive (Goschy et al., 2014; Kabata & Matsumoto, 2012) and may work together to aid visual search. A recent study by Goschy et al. (2014) investigated whether probability cueing of *distractor* locations (rather than target locations) was possible. Over the course of three experiments, participants were asked to find the target amongst several distractor items, including a singleton distractor which was salient in colour. In Experiments 1 and 3, the singleton was manipulated to appear 90% of the time on one side and 10% on the other. In Experiment 3, it was equally as likely to appear on either side of the array but could repeat across different

locations within trials. When statistical learning and intertrial repetition priming were enabled, probability cueing effects were observed, and distractors in highly probabilistic locations were less likely to cause interference during visual search. On the other hand, when repetition priming was inhibited or when statistical learning was avoided by inducing an even probability of the distractor locations across the search array, probability cueing effects were abolished and distractor interference was detected. Unlike the aforementioned studies, these results suggest that both statistical learning and intertrial repetition priming work together to bias search and visual attention in a beneficial way. However, it is important to note that these results were observed when studying distractor probability so may only be generalised to this design rather than target probability cueing.

To summarise, the extent to which intertrial repetition priming or statistical learning contribute to spatial learning is unclear (Jones & Kaschak, 2012; Kabata & Matsumoto, 2012; Shaqiri & Anderson, 2012). Some researchers have proposed that both work together to induce probability cueing effects (Goschy et al., 2014; Kabata & Matsumoto, 2012) whereas other researchers have concluded that the two have individual effects on search behaviour (Geng & Behrmann 2002, 2005; Jones & Kaschak, 2012; Stankevich & Geng, 2014; Turk-Browne, Jungé, & Scholl, 2005; Walthew & Gilchrist, 2006). Even so, probability cueing seems to be a replicable effect which, however, can be extremely susceptible to small variations and manipulations in experimental designs.

1.1.3 Probability cueing in large-scale space

It has been argued that visual search tasks represent a good model for large-scale, real-world search behavior, including natural 'foraging' search (Klein & MacInnes, 1999; Thomas et al., 2006; Wolfe, 1994). These researchers go so far as to argue that the mechanisms used to undertake visual search are the same as real-world search, even though there are clear differences between the two. **Table 1.1** details some of these differences.

Table 1.1 Differences between laboratory visual search tasks, and real-world search.

Traditional visual search tasks	Real-world search
Items are randomly distributed and are equally as likely to appear across many locations.	Objects are less likely to be randomly distributed i.e. appear in predictable locations.
Items tend to be isolated from a context.	Objects tend to be incorporated within a complex context.
Items are clearly visible.	Objects can be cluttered or overlaid. This may require multiple actions to bring the object into view.
Only requires eye movements to search.	Requires full body movements (including eye, head and body) to search the environment, requiring live spatial updating.
Does not require a 'sense of direction' to search for the target.	Requires a 'sense of direction' if full body movement is needed.
Items are placed in the observer's immediate field of view ('near space'), within a single plane.	Items may be extended beyond a single field of view ('far space'), in three dimensions, with depth.
May take a minimal amount of time to search the whole array (i.e. milliseconds).	May take a reasonable amount of time to search for an object due to extension of space beyond a single field of view (i.e. seconds; minutes).

Although studies of human search behaviour have primarily used variants of the visual search paradigm, some research groups have studied search behaviour under realistic circumstances. For example, Foulsham, Chapman, Nasiopoulos and Kingstone (2014) found that participants used whole-body, head and eye movements to search for a target 'mailbox' rather than remaining static and using eye movements alone. They also found that, unlike in visual search tasks, target saliency has little effect on search behaviour, unless participants are told specifically what the target mailbox looked like. Other research has also indicated that rechecking locations for hidden targets is rare in large-scale search in comparison to visual search tasks, suggesting a more enhanced use of memory in real-world search (Gilchrist, North, & Hood, 2001).

Recent probability cueing experiments using large-scale apparatus have indicated that efficient search in this context requires the addition of many factors (Jiang, Won, Swallow & Mussak, 2014; Smith, Hood, & Gilchrist, 2010). Unlike visual search, large-scale probability cueing may operate at a conscious level, meaning that participants are more likely to be aware of the target's most probable location across trials (Smith et al., 2010). These studies will not be discussed.

One spatial factor that visual search tasks do not necessarily tap into, are reference frames. Reference frames refer to whether different locations, targets, objects and environments are computed and represented to the individual in viewer-centred (egocentric) or external object-centred (allocentric) coordinates (Burgess, 2006; Smith et al., 2010). Spatial updating is defined as the automatic process associated with this coding (Byrne, Becker, & Burgess, 2007). It has been suggested that spatial updating can occur using egocentric, allocentric or both reference frames (Burgess, 2006). There

is a variety of evidence from animal research (Paul, Magda, & Abel, 2009), neuroimaging methodologies (Zaehle et al., 2007) and behavioural tasks (Burgess, 2006) that suggested reference frames are actively used to aid spatial navigation and memory.

Traditionally two-dimensional (2D) visual search tasks do not allow researchers to investigate the combination of egocentric and allocentric reference frames because no physical movement is possible (Jiang & Swallow, 2013). This was, however, examined by Jiang and Swallow (2013) who presented probabilistically manipulated stimuli on a flat tabletop monitor (i.e. in the transverse plane). Three experiments were conducted in which a 'T' target was presented, amongst eleven 'L' shape distractors. The training phase had an uneven target location probability manipulation – 50% of the time the target appeared in one of the four quadrants (rich region) and 16.7% of the time it appeared in one of three others (sparse region). In the testing phase the target appeared evenly across the four quadrants.

Jiang and Swallow (2013) used three variations of the experimental task. In Experiment 1, participants were asked to complete all trials in the training phase and then move their seating position by 90° for the testing phase. In line with visual search studies (e.g. Geng & Behrmann, 2002; Walthew & Gilchrist, 2006) RT was faster in the rich region of space, indicating sensitivity to this statistical contingency. Participants were also unaware of the target location manipulation. However, as the participant changed their seating location, they continued to bias search to the high probability area, even though this position was now a sparse region. Experiment 2 also revealed similar results, suggesting that a salient landmark (the rich region clearly

indicated by illuminating the side of the square) did not make a difference to the coding of this bias. This result is comparable to the results of Foulsham et al. (2014), of whom found that increasing the saliency of a target did not affect large-scale search behaviour unless participants were explicitly told that the target was a specific colour. Experiment 3 further suggested that limiting saccadic eye movements (thus limiting the use of an egocentric reference frame), by presenting the stimuli for an extremely brief amount of time (180ms), did not enhance the use of an allocentric reference frame. The probability cueing effect was prominent and was coded in an egocentric reference frame only. Together, the authors took these results to indicate that effective search and the allocation of spatial attention uses a purely egocentric reference frame.

In a more recent study, Jiang and colleagues (2014) aimed to manipulate the use of different reference frames in a large outdoor environment. In this study, participants were asked to stand in the centre of an outside area and to indicate whether a coin placed on the floor was facing upwards in silver or black. Each four sides of the environment were marked via prominent landmarks: picnic benches, a river/road or two distinct university buildings. Participants did not move from the start position, and probability cueing was introduced in the same quadrant patterns as Jiang and Swallow (2013); 50% (cued): 16.7% (uncued). In the first experiment participants always started facing the same direction on each trial, to align both egocentric and allocentric reference frames. In the second and third experiment, participants were randomly assigned a start direction on each trial. In the second experiment, the cued quadrant was fixed according to environment-based coordinates (e.g. it was in the quadrant facing the river). In Experiment 3, the cued quadrant was instead fixed in body-based coordinates, so that

it appeared according to the participants starting direction (e.g. it was consistently the quadrant to the participants front right, no matter what environment-based coordinates this position encompassed).

Jiang et al. (2014) found evidence of probability cueing under all conditions, even when trials that contained targets within successive repeats of the quadrant were isolated, and analysis was conducted on all trials containing infrequent target repetitions. In line with visual search tasks, they also found most participants were unaware of the target's probable location. The finding that probability cueing occurred even when trials containing consecutive repetitions of the target in the cued quadrant were isolated, indicates that probability cueing in large-scale environments may not be due to short-term repetition priming. The findings also indicate that search in this context is flexible, and can use both singular and combined reference frames to efficiently operate within.

On the other hand, Smith et al. (2010) examined the probability cueing effect in relation to a large-scale, three-dimensional (3D) full-body search task. The aim of the task was to find the target, by pressing illuminated floor buttons. The target was indicated by a colour change (from green to red). Targets were manipulated to appear more on one side of space than the other (80%:20%). Six experiments were designed, in which a slight manipulation in the design meant several different spatial and perceptual combinations were tested. **Table 1.2** describes the design and results for each of the experiments conducted within this research.

Table 1.2 Details of the various factors manipulated during each experimental design tested in a large-scale probability cueing task, by Smith et al. 2010.

Experiment	Factors tested	Method	Probability cueing present?
1	Egocentric features consistent; allocentric features manipulated.	Start position consistent; display was extinguished between trials and a new array reappeared.	No
2	Egocentric and allocentric features consistent.	Start position consistent; array consistent and was not extinguished between trials.	Yes
Interim conclusion: Probability cueing may rely on the consistency of allocentric coordinates as changing allocentric features was detrimental to learning.			
3	Egocentric features manipulated; allocentric features consistent.	Start position randomised; array was not extinguished between trials and was defined in room-based coordinates.	No.
4	Egocentric features consistent; allocentric features manipulated.	Start position randomised; array was not extinguished between trials and was defined in body-based coordinates.	No.
Interim conclusion: When reference frames are used in isolation, probability cueing does not occur.			
5	Egocentric features manipulated; allocentric features consistent. Additional landmark feature included to test spatial or perceptual basis.	Start position randomised; array was not extinguished between trials; array visibly separated by two colour cues, defined in room-based coordinates.	Yes.
6	Egocentric features consistent; allocentric features manipulated. Equal distribution of target (no spatial component); instead associated with a colour (perceptual component).	Start position randomised; array was not extinguished between trials and was visibly separated by two colour cues; the cued side colour was defined in body-based coordinates.	No.
Interim conclusion: Probability cueing relies upon spatial coordinates.			
Overall conclusion: Probability cueing relies on a combination of spatial cues.			

In contrast to Jiang and colleagues (2014), Smith et al. (2010) concluded that efficient search requires a combination of allocentric and egocentric reference frames, and that egocentric consistency alone did not support probability cueing. For example, in Experiment 2, the search array remained fixed throughout and the participants' start position was in the same location across all trials. Efficient probability cueing was observed, unlike when the array changed across trials (Experiment 1). This is in line with recent work from the spatial memory literature, which suggests that effective spatial updating and mental exploration require a combination of both reference frames (for a review see Byrne et al., 2007). Smith et al. (2010) also found that participants expressed an awareness of the probability cue. This is unlike the results of visual search experiments (e.g. Geng & Behrmann, 2002), in which the probability cueing effect has always been observed as implicit. Results from other studies that have used ecologically valid stimuli, such as natural scenes, have also suggested that search involves conscious awareness (e.g. Brockmole & Henderson, 2006; Rosenbaum & Jiang, 2013). However, these studies do not conform to probability cueing paradigms.

There are several reasons for the differences in results between Jiang et al. (2014) and Smith et al. (2010). Although Jiang et al. (2014) used a large outdoor environment, their task is still like a visual search task; no physical movement (apart from a full-body turn between trials) was involved. This may have been why participants did not report any awareness of the cue. Participants were also instructed to close their eyes between trials, meaning there was no secure way of knowing that they were not watching the Experimenter place the coin between trials. On the other hand, the large-scale apparatus used by Smith et al. (2010) is based on foraging search,

involving effort and full-body and head movement. The large-scale apparatus was also controlled and consistent, surrounded by a black out curtain, unlike the outdoor environment used by Jiang et al. (2014) in which viewpoint changes also incurred a different visual landmark. This change in landmark may have helped participants with reorientation, aiding the use of a singular reference frame.

Overall, probability cueing in large-scale space has rarely been studied and the results from the two published experiments that have exploited this set-up, are mixed and difficult to compare. In this next section, the potential candidate regions defining the neuronal basis of probability cueing will be discussed.

1.1.4 Neuronal basis of probability cueing

The neuronal basis of probability cueing is largely unknown and has not yet been systematically investigated. There has, however, been a selection of studies using functional magnetic resonance imagining (fMRI) to decipher the underlying correlates of statistical learning and intertrial repetition priming in visual search tasks (e.g. Kristjansson, Vuilleumier, Schwartz, Macaluso, & Driver, 2007; Turk-Browne, Scholl, Chun, & Johnson, 2009). These studies suggest that the right hemisphere may play a prominent role in attentional cueing. Furthermore, patients who have lesions to their right hemisphere tend to demonstrate marked attentional deficits (Heilman & Valenstein, 1979; Husain & Rorden, 2003; Kinsbourne, 1987). Although these studies are not specific to probability cueing, the possibility of right hemisphere involved in this attentional process will now be explored.

1.1.4.1 Hemispatial neglect

Hemispatial neglect is a multifaceted disorder, characterised by impairments in a variety of cognitive and spatial processes (Husain & Rorden, 2003). Hemispatial neglect is primarily demonstrated by a failure to orient attention to the contralesional side of space, meaning that, for example, a right hemispheric lesion may create a failure to detect people, objects or own body parts located within the left side of space. This occurs even though the patient is not visually impaired. It has marked localised effects, primarily indicating that lesions to the parietal lobe are most frequently related to symptoms (Halligan, Fink, Marshall, & Vallar, 2003). Lesions are often a result of stroke and if they are localised in the right parietal areas, patients are more likely to endure neglect than those who have lesions in the left parietal areas (Husain & Rorden, 2003). However, other lesioned areas such as the temporparietal junction or the ventrolateral prefrontal cortex can contribute to neglect effects, but again, effects tend to be greater if lesions are within the right parietal cortex (RPC) (Karnath & Rorden, 2012).

Animal and human studies have suggested that the spatial deficits associated with neglect may be due to the contralesional hemisphere exerting an increased inhibition onto the damaged hemisphere (e.g. Kinsbourne, 1987; Lomber & Payne, 1996). The classic model of Hemispheric Rivalry (Kinsbourne, 1987) assumes that the intact brain reciprocates inhibitory neural activity between hemispheres to keep it at equilibrium and determine the direction of attention. In patients with hemispatial neglect, this process is disrupted and the intact hemisphere is constantly hyperactive whilst the lesioned hemisphere is inhibited. The hyperactive state of the intact

hemisphere causes it to have greater control over attention and results in neglect to the contralesional side of space (ipsilateral to the intact hemisphere). Hence, presentation of a stimulus activating the intact hemisphere leads to further suppression of the lesioned hemisphere and a reduction in the 'perceptual weight' of the presented stimulus (Bisley & Goldberg, 2010). This imbalance can occur in either hemisphere, however it is more significant when damage occurs to the right hemisphere because it naturally exerts a smaller bias to the left hemifield.

In contrast to this account, Heilman and colleagues (1979; 1980) propose that the right hemisphere naturally mediates attention across *both* hemifields. The left hemisphere is important for attention directed towards the right hemifield. If the left hemisphere becomes damaged, the spatial attentional deficits associated with it are therefore lessened because the right hemisphere can still contribute towards allocating attention across both hemifields. In comparison, when the right hemisphere is damaged, greater attentional deficits are caused as both hemifields become cancelled out, leaving the right hemifield to become dominant.

Although both theories (see **Figure 1.1**) are slightly different in nature, what is important to point out is that both describe functional asymmetry and a balance between activation in the hemispheres within healthy populations. The right hemisphere clearly plays a strong role in the allocation of spatial attention as exemplified by the fundamental effects it has on those who experience hemispatial neglect.

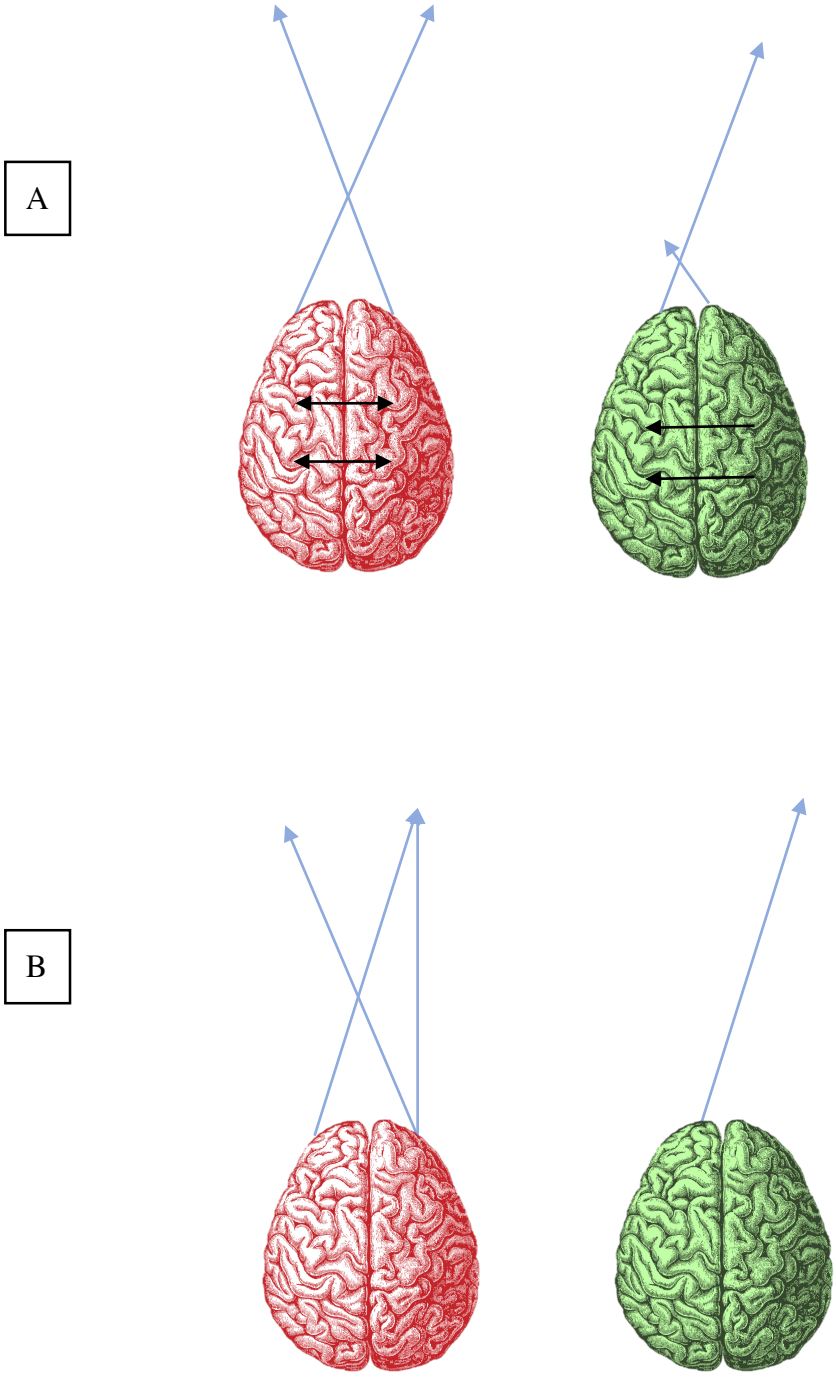


Figure 1.1 **A:** Kinsbourne (1987). *Left*: In the intact brain, inhibition keeps the two hemispheres in equilibrium. *Right*: When the right hemisphere is lesioned, it becomes hyperactive and the left hemisphere becomes more inhibited, causing the effects of hemispatial neglect. **B:** Heilman and colleagues (1979; 1980): *Left*: In the intact brain, the right hemisphere controls left and right hemifields whereas the left hemisphere controls the right only. *Right*: When the right hemisphere is lesioned, the left hemifield is neglected and the left hemisphere controls the right hemifield only.

1.1.4.2 Hemispatial neglect and probability cueing

Overall, the attentional deficits observed in patients with hemispatial neglect suggest that the right hemisphere is important for the allocation of attention. Thus, if probability cueing relies on biasing search and attention towards a particular hemifield, then one might predict that this hemisphere may be heavily involved with learning and search efficiency.

A recent study by Shaqiri and Anderson (2012) tested patients with hemispatial neglect, as well as patients with more generalised right hemisphere damage, during a probability cueing task. A key point to highlight here is that although parietal lobe damage is the most common neural correlate of hemispatial neglect (Halligan et al., 2003), it is not the only brain area to influence symptoms of the neurological disorder (Karnath & Rorden, 2012). Therefore, Shaqiri and Anderson (2012) aimed to assess whether patients with right hemisphere lesions would demonstrate probability cueing effects, and whether those with or without neglect would show differential search performance. The target (a white or black dot) was manipulated to appear in a 'cone shaped' distribution; participants had to respond to the colour of the target. 75% of the time the target appeared on the left, in a 'hot spot'; 12.5% of the time it appeared on the right in a 'warm spot' and for another 12.5% of the time, it appeared within the 'background' on either side of the search array. Distractors were not presented to prevent neglect patients becoming fixated with distractors on the ipsilesional side of space.

The paradigm specified by Shaqiri and Anderson (2012) meant that the target could appear at many locations, allowing the assessment of both intertrial repetition

priming and statistical learning. To analyse intertrial repetition priming, trials in which the target repeated within the same area or near to each other were isolated and compared to trials in which the target did not consecutively repeat. Results suggested that during repeated trials, healthy controls showed a significant RT decrease. Patients who did not have neglect, also showed this effect but to a lesser extent. Strikingly, the RT benefit during repeated target locations was absent for hemispatial neglect patients, suggesting behavioural differences between the two patient groups. This effect also did not change as the number of consecutive repetitions increased. Thus, neglect patients were unable to bias their search towards the cued side, when the target repeated in the same location across trials. This result suggests that the absence of intertrial repetition priming in neglect patients is most likely due to the presence of the attentional deficit induced by damage to the right hemisphere, rather than a specific brain region per se.

When examining statistical learning, it was demonstrated that healthy controls learnt that the target was more likely to be on one side of the array than the other and, more specifically, targets within the hot spot area were processed quicker than targets presented in other areas. Right hemisphere patients who did not have neglect also showed a global learning effect, but further examination of results revealed that they were not faster at identifying the hot spot in comparison to other background locations. These results are in line with those of Jones and Kashak (2012), who suggest that probability cueing relies on processing of global statistical features in the absence of repetitions.

Shaqiri and Anderson (2012) also found that neglect patients were faster to respond to targets when they were located within the hot spot than on the high

probability side of the search array. This suggests that probability cueing was partially intact even though high probability targets could have been presented on the neglected side of space. This emphasises the core involvement of the right hemisphere, rather than a specific brain region. This finer analysis highlights the complex nature of neglect and its interaction with probability cueing.

Conducting the same study with patients who do and do not present neglect after a left hemisphere lesion may offer insight into whether probability cueing is specifically reliant upon the right, rather than the left hemisphere. Although probability cueing seems to be intact in patients who present spatial deficits, it works in a manner that it is 'tuned down', suggesting that the right hemisphere may hold part of an attentional system, aiding the bias of search towards highly probabilistic regions. Shaqiri and Anderson (2012) also provide evidence to suggest that neglect patients do not simply use the repetitive nature of a target's location to learn the probability cue; instead, their research suggests that probability cueing is mediated by statistical learning.

Another point to highlight here is that although the results from the intertrial repetition priming analysis suggest that probability cueing may not necessarily be localised to a specific brain region within the right hemisphere, other studies have reached alternative conclusions. For example, Kristjánsson et al. (2007) found that location repetition priming led to a reduction in blood oxygen level- dependent activity in the right inferior and anterior parietal regions, regardless of the hemifield that the target appeared within. Furthermore, there has been fMRI studies that have demonstrated the role of the RPC in statistical learning. Turk-Browne et al. (2009) found that the right interior parietal lobule showed a stronger response during the final

blocks of trials in which the target's location was structured, rather than randomised. This evidence is in line with Kinsbourne's (1987) and Heilman and colleague's (1979; 1980) accounts that suggest that the right hemisphere plays a substantial role in the allocation of attention. More recent theories have expanded upon the concept of hemispheric rivalry to implicate the primary role of the RPC in attention (see **Section 4.1** for an account of these: Bisley & Goldberg, 2010; Corbetta & Shulman, 2002).

Theoretically, if probability cueing within visual search is controlled by an attentional system within the RPC, this system could also underpin cueing in large-scale space. Although it has not been tested directly, the work by Smith et al. (2010) indicates that high order brain areas may be involved in efficient probability cueing under this context. This is because large-scale search involves full-body movements into extrapersonal space, rather than saccades (Geng & Behrmann, 2002). The complexity (i.e. a static egocentric viewpoint, 2D visual search vs. a constant viewpoint change, 3D large-scale search) and the differences between the action outputs (i.e. button press vs. full-body movement) insinuates that the RPC could be a potential candidate region for large-scale search, supporting the allocation of attention in this type of environment. This has been confirmed in many functional neuroimaging studies, which have identified the RPC as having core engagement in virtual environment tasks requiring similar spatial attention demands as real-world search tasks (e.g. Hampstead, Brown, & Hartley, 2014; Maguire et al., 1997; Spiers & Maguire, 2006). The following section will describe in detail how the parietal lobe has been manipulated using brain stimulation, to demonstrate its contribution to spatial attention and search behaviour.

1.2 Manipulations of spatial learning

Over several decades, various technological advances have occurred, creating neuroimaging and neuro-stimulatory techniques with relatively good temporal and spatial resolutions. An advantage of these techniques is that they are useful for investigating brain-behaviour relationships, meaning that the neuronal basis of probability cueing could be resolved. Reversible models of impaired spatial attention and search behaviour, such as that characterised by hemispatial neglect, can be produced easily and effectively in healthy subjects using these techniques. This is achieved by temporarily modifying the excitation or inhibition of brain regions undergoing stimulation. In this next section, transcranial direct current stimulation (tDCS) will be discussed. Although no research group to date has used this technique to manipulate probability cueing, other tasks that tap into spatial attention and general search behaviour have been examined. In sum, these studies suggest that the RPC is particularly important for effective search behaviour and allocation of spatial attention (for a review see: Harvey & Kerkhoff, 2015). A brief definition of both techniques will be followed by a selection of studies that have manipulated spatial learning or attempted to improve it in hemispatial neglect patients.

1.2.1 Transcranial direct current stimulation (tDCS)

tDCS involves emitting a weak, direct current to cortical region(s) of the brain, via two large electrode pads (see **Figure 1.2** for tDCS equipment). The current can modulate cortical activity, causing a parallel change in behaviour (Nitsche et al., 2008). tDCS modulates the resting membrane potential of neurons in different directions, via anodal or cathodal stimulation. Generally, experimental results suggest that anodal

stimulation depolarises neurons, which increases the probability of neuronal firing; whereas cathodal stimulation has an opposite effect, hyperpolarising neurons and decreasing the probability of neuronal firing (Nitsche & Paulus, 2000). tDCS has been shown to have an effect on cognitive functions including memory, attention and learning processes (for a review see Coffman, Clark & Parasuraman, 2014).

1.2.1.1 Mechanisms of action

Little is known about the cellular mechanisms of action during or after tDCS. In the early 1960s, Bindman, Lippold and Redfearn (1964) demonstrated that anodal stimulation increased spontaneous neuronal firing whereas cathodal stimulation had the opposite effect. However, this and other experimental animal studies conducted around the same time (e.g. Purpura & McMurtry, 1965) used electrodes that were in direct contact with the cortical surface; this is unlike human experiments, in which the electrode is in contact with the scalp. Human tDCS experiments have instead suggested that as little as 10% of current enters the brain via scalp electrodes (Rush & Driscoll, 1968), although more recent research has suggested that the percentage of shunting is effected by the electrode dimension and position (Miranda, Lomarev & Hallett, 2006). Even so, pronounced effects of tDCS on cognitive tasks have been found (Jacobson, Koslowsky, & Lavidor, 2012; Kuo & Nitsche, 2012) and modelling current flow has also offered a good insight into the effects of tDCS on the cortical surface (Miranda, Faria, & Hallett, 2009; Miranda et al., 2006; Miranda, Mekonnen, Salvador, & Ruffini, 2013).



Figure 1.2 tDCS equipment. From bottom left to the top: Washable pen, measuring tape, rubber electrodes, electrode cables, conductive gel, sponge electrode pads, tDCS stimulator, tDCS parameter programmer, power cables (grey and black), tight fitting cap.

Recent research has offered insight into the neurophysiological mechanisms of tDCS. The effects of tDCS can be measured during stimulation (online) or after stimulation (offline), as tDCS produces after-effects. During online stimulation, it is thought that tDCS alters the membrane potential of the cells underneath the electrode

pad. This is evidenced from the aforementioned animal studies, but also from human studies. Drugs can be administered that temporarily block sodium channels (carbamazepine) and calcium channels (flunarizine). During anodal tDCS, Nitsche et al., (2003) found that both flunarizine and carbamazepine abolished the facilitatory effects associated with this type of stimulation. However, there was no effect of either drug during cathodal stimulation. This is in line with the animal studies, insofar as blocking sodium and calcium channels means that the hyperpolarisation effect of anodal stimulation is diminished. On the other hand, when sodium and calcium channels were forced to close, neurons were instead hyperpolarised, negating the effect of the drug and allowing the cathodal effects.

Offline protocols have revealed a slightly different account of tDCS mechanisms. Instead, post-stimulation changes are due to synaptic plasticity effects (particularly GABA and glutamate systems), as well as alterations in the membrane potential (Stagg & Nitsche, 2011). Nitsche et al. (2003) also tested the offline effects of tDCS and found that carbamazepine and flunarizine abolished anodal after-effects too, suggesting that changes in membrane potential may play a role in offline tDCS effects. However, the authors also found that dextromethorphane (an NMDA antagonist, blocking the glutamate receptors) also abolished anodal and cathodal after-effects. These changes in synaptic plasticity and membrane potential mean that tDCS may influence learning and memory (Kim, Stephenson, Morris, & Jackson, 2014), akin to the long-term potentiation effects that allows synaptic plasticity in the cortex (for a review see Stagg and Nitsche (2011)).

tDCS involves many experimental parameters including: electrode size (cm^2) and shape, current intensity (milliamps – mA), duration of stimulation and electrode positioning. These parameters, and others, are detailed in **Section 2.2**, but briefly, it is important to note that during stimulation an anodal and cathodal current are always present. One electrode is referred to as the 'active electrode' and is positioned over the region of interest, whereas the 'reference electrode' tends to be positioned over an area that has 'minimal effects' on the task being undertaken. Many researchers counterbalance these electrodes, so that during one condition the active electrode may emit an anodal current, and the reference a cathodal current, and vice versa. Different size electrodes can also help to reduce the effects of reference electrode, whilst focusing the active electrode current (Nitsche et al., 2007). However, this is not common practice, nor is it standard to include a sham, control condition in tDCS experiments.

1.2.1.2 Manipulations of search behaviour and spatial attention

To date there have been no studies that have examined probability cueing and tDCS. However, there have been a few that have examined its effects on search behaviour, during and after stimulation to the RPC. Ball, Lane, Smith, and Ellison (2013) used a simple conjunction visual search task to investigate whether tDCS could enhance target detection. A pair of $35cm^2$ electrodes were positioned on the RPC and the left frontal eye fields, and respective anodal and cathodal stimulation was delivered in a counterbalanced manner. Participants completed one block of the conjunction search task before the stimulation, then another during the 15 minutes of stimulation, followed by two blocks post-tDCS. Results suggested that as the experiment

progressed, participants who received cathodal to the RPC (hereafter, CRPC) had slower RTs than any other group.

Ball et al. (2013) later followed this tDCS study with an fMRI investigation (Ellison et al., 2014) to more accurately examine which brain areas were manipulated following the tDCS set-up. Unlike the previous study, Ellison and colleagues (2014) used an offline tDCS protocol in which tDCS was given to each participant, which was then followed by completion of the conjunction search task during scanning. The Researchers replicated their previous results, by finding elevations in RT when CRPC was emitted. CRPC significantly decreased activity in the frontal lobe across left and right hemispheres. There was no change in activity in the RPC, nor was there any significant activity changes during block two of the visual search task. The authors concluded that the changes in frontal lobe activation indicated that CRPC causes a network change in the frontal regions. However, they do not consider that anodal stimulation to the frontal eye fields may be the reason for this significant change. Although it is assumed that cathodal stimulation inhibits neuronal activation, it has been shown that anodal can have similar effects (Jacobson et al., 2012), and thus in this case, this electrode montage paired with this task, may have resulted in unpredictable anodal effects. It is also difficult to decipher whether cathodal or anodal are driving the effects as both electrode sizes were the same, meaning the strength of the electric field created by tDCS (current density) was the same under both pads.

Clark et al. (2012) also examined the role of the RPC in a search task using tDCS. This time, a 'discovery learning paradigm' was used, in which participants were shown realistic static images and asked to detect whether a concealed target was present

or absent. These images were screen shots from a virtual reality environment that is used for military training. Participants firstly completed a training block during fMRI, in which the RPC was identified as a key brain area involved in the task. This was then followed by another training session during which anodal tDCS to the RPC (hereafter, ARPC) was administered (the reference electrode was positioned on the upper forearm). ARPC enhanced learning on the task, by increasing accuracy of target identification by 22.50%. This effect was found only for 2mA strength - an intermediate current strength of 0.6mA and sham strength of 0.1mA had no effect on learning. Furthermore, the effects of ARPC lasted approximately 90 minutes after stimulation. This result has since been replicated (e.g. Coffman et al., 2012; Falcone, Coffman, Clark, Parasuraman, & Miller, 2012). Together, these studies provide strong rationale for the investigation of tDCS in the enhancement of spatial learning and target identification under naturalistic statistical restraints.

The effects of tDCS on spatial attention have also been studied. Li et al. (2015) investigated the effects of 'dual tDCS' on four different tasks: number comparison (measuring numerical processing), modified Posner cueing task (measuring spatial attention), choice reaction task (measuring information processing and sustained attention), and a rapid visual processing task (measuring sustained attention). Dual tDCS involves the application of two same sized electrodes ($25cm^2$, in this case) delivering both anodal and cathodal, that are positioned in homologous brain regions (left and right parietal cortices, respectively). Dual stimulation can also involve actively stimulating two brain regions at the same time, with a reference electrode elsewhere (e.g. Sparing et al. (2009)). Li and colleagues (2015) firstly trained participants on all

four experimental tasks. This was then followed by three tDCS sessions that were 48 hours apart: sham tDCS, anodal left parietal cortex/CRPC (ALPC/CRPC) or cathodal left parietal cortex/ARPC (CLPC/ARPC). During each session, the tasks were completed in the following order, after 10 minutes of the tDCS being switched on: number comparison, modified Posner cueing task and choice reaction task. tDCS was then switched off and the rapid visual processing task was completed. The authors provide no reasoning for this task order, nor was it counterbalanced across sessions or within participants.

Of relevance to this Thesis, the Posner cueing task has been demonstrated previously as a valid measure of spatial attention and to have strong associations with the RPC. In a modified version of the Posner cueing task, Li et al. (2015) firstly showed participants a fixation cross which varied in its length of time on screen (500-3000 milliseconds). This was then followed by different cue conditions. In the *no cue* condition, a square target appeared on the left or the right side of the screen and participants had to respond to indicate the hemifield it appeared within. In the *alerting* condition, before the target appeared, a double-headed arrow was displayed, alerting participants to the forthcoming target. In the *valid cue* condition, a directional arrow was displayed, again before the target appeared. This arrow was valid on 80% of trials, meaning it accurately directed the participants' attention towards the target's location. Finally, in the *invalid cue* condition, a directional arrow appeared, to draw attention towards the incorrect target location. This invalid arrow was shown on 20% of trials. The tDCS results from this experiment only will be discussed.

Li et al. (2015) found a general effect during the Posner cueing task: fastest RTs were achieved during the valid cue condition, followed by the alerting cue, invalid cue and finally the no cue condition. However, tDCS did not modulate any cueing effects, nor did stimulation incur any hemifield biases. Although this result suggests that under these tDCS conditions, stimulation cannot modify spatial attention, there may be several methodological reasons why this occurred. Participants were firstly trained on the Posner cueing task, and in total they completed the task four times. It has recently been suggested that tDCS is particularly effective when cognitive load and difficulty is high (Berryhill, Peterson, Jones & Stephens, 2014). Training and exposure may have reduced the cognitive load of participants, encouraging ceiling effects, hence tDCS may have had minimal influence on performance.

Secondly, it has been suggested that if an irrelevant or unrelated task is undertaken during or directly after stimulation (Gladwin, den Uyl, Fregni, & Wiers, 2012; Horvath, Carter, & Forte, 2014; Quartarone et al., 2004) then this can cause interference, which in turn abolishes or changes polarity-specific effects. For example, Nozari et al. (2014) found a facilitatory effect of cathodal stimulation on the Flanker task (post-stimulation) when an unrelated task was performed during stimulation. However, when participants completed a task posing the same cognitive demands as the Flanker task during stimulation, an inhibitory effect of cathodal stimulation resulted. Before the Posner cueing task, the number comparison task was performed which may have interfered with the stimulatory effects relating to the Posner cueing task. Significant stimulatory effects were found on the number comparison task, with ARPC/CLPC demonstrating reduced RT responses in comparison to sham.

Counterbalancing the order of the tasks between and within participant testing sessions may have counteracted this potential interference effect, although at the cost of adding more factors into the experimental design.

In comparison to Li et al. (2015) other research groups have found effects of RPC tDCS on spatial attention (for reviews see: Coffman et al., 2014; Harvey & Kerkhoff, 2015). RPC tDCS can induce hemifield biases (e.g. Benwell, Learmonth, Miniussi, Harvey, & Thut, 2015; Sparing et al., 2009). Sparing et al. (2009) found that 15 minutes of 1mA offline ARPC tDCS (reference: central point of the skull) biased attention towards the left side of space in healthy subjects. Behaviourally this effect was evidenced by a higher target detection to the left side of space. ALPC tDCS also incurred contralateral effects, with a higher target detection to the right side of space. Contralateral, inhibitory effects were instead found with cathodal stimulation, for example, CRPC stimulation inhibited left-sided target detection. Furthermore, targets that appeared ipsilateral to stimulation were detected at similar rates, emphasising the powerful induction of specific contralateral hemifield bias during stimulation. No effects of cathodal tDCS were found when examining RT as a measure of performance. There were, however, effects of anodal tDCS, suggesting that RT decreased for targets both ipsilateral and contralateral to stimulation; the effect was global. In total, this research suggests that stimulation to parietal regions could enhance search performance, influencing sensitivity to hemispace differences in search arrays. However, effects are subtle, as evidenced by tDCS influencing the accuracy of target detection rather than the speed of response.

Sparing et al. (2009) also examined the effects of tDCS in hemispatial neglect patients. All patients had lesions to their right hemispheres, causing the associated neglect effects to the left side of space. Two different tasks were used: a neglect subtest and the line bisection task. In the neglect subtest, participants were required to press a button when a flickering target was detected. The authors found that anodal tDCS to the left and right parietal cortices enhanced RT to the left visual field; however, there was a greater effect when stimulation was targeted within the RPC (the lesioned hemisphere). Patients also completed a line bisection task. For this task, ARPC tDCS was associated with a reduction in rightward biases. CLPC tDCS was also associated with the same effect. These results suggest that tDCS effectively biased attention towards the neglected hemifield.

More recent research has now been conducted with hemispatial neglect patients, although its potential use as a rehabilitation tool is still open to debate (for a review see Müri et al., 2013). For example, a study by Smit et al. (2015) suggested that it is not feasible to test hemispatial neglect patients because of the strict health and safety guidelines that recruitment involves. In total, 65 patients were excluded from their clinical trial because of the associated high risks of stroke relapse or interference with comorbidities. The six patients that did participate did not experience any long-lasting improvements in neglect symptoms after their tDCS treatment plan. However, the work by Sparing et al. (2009) and others (e.g. Sunwoo et al., 2013) suggest that neglect symptoms may only be relieved immediately post-stimulation; the effects of stimulation may therefore be short-lived and ineffective as a long-lasting rehabilitation

tool. Further investigations are needed to examine the safety and behavioural effects of several, on-going brain stimulation sessions over a long time period.

Overall, results from tDCS studies are mixed. Some tDCS experiments suggest that the RPC independently plays a fundamental role in search behaviour and attention (e.g. Sparing et al., 2009) whereas others suggest that its connectivity to other regions may be of more thorough importance (e.g. Ball et al., 2013; Ellison et al., 2014). Even so, tDCS has proved useful for examining the underpinnings of such cognitive behaviours. These neurocognitive techniques allow researchers to easily investigate how a healthy brain can become temporarily altered causing powerful behavioural effects on simple tasks. On the other hand, they also demonstrate the potential use of such techniques to transiently modify neuronal activity to enhance desirable behaviours.

1.3 Thesis overview

Probability cueing is a paradigm that has been studied using large-scale and pure visual search paradigms. During large-scale search, participants need a variety of stable spatial cues to make *explicit* inferences concerning the spatial likelihood of a target's location. In contrast, under simple visual search constraints, participants can more easily bias their search, in a manner that appears to be *implicit*. Further to this, the neural underpinning of probability cueing is currently unknown, although brain stimulation studies have demonstrated that the RPC may play a role in the allocation of spatial attention, alluding to the possibility that efficient probability cueing may require input from this brain region. Patient studies have also suggested right parietal

involvement, with results from hemispatial neglect patients demonstrating an attenuated cueing effect.

In Chapter 2, the general methodology for this Thesis will be introduced, including the design and layout of the probability cueing tasks and the parameters and experimental set-up of tDCS. Chapter 3 will outline three experiments that have examined probability cueing within a new environmental context: virtual, simulated environments. Behaviour elicited within virtual environments is increasingly being examined within research and industry, and is thought to model real world behaviour. It is therefore fundamental that search behaviour is studied under this context, to examine whether its sensitivity differs from visual search and full-body search. Virtual environments allow probability cueing to be examined under 3D contexts, without some of the artefacts or difficulties that arise with real-world or large-scale laboratory environments, such as the necessary space. It also means that physical effort is removed, meaning that more trials can be presented to participants. The removal of physical effort is akin to visual search, whereas the depth and scale of the environment means it is equivalent to large-scale search. Arguably, virtual environments are therefore a medium between the two contexts. The first two experiments will introduce the virtual environment using a monitor display. This is then followed by an investigation into whether increasing the immersive qualities (in terms of display size) influences probability cueing. The final experiment within Chapter 3 attempts to replicate the results from the large-scale foraging study conducted by Smith et al. (2010) using a laboratory space with search items presented on the floor.

Chapter 4 will detail experiments that addressed whether it was possible for probability cueing behaviour to be transferred between environments; in this case, from a virtual world into a laboratory environment. The transfer of efficient behaviour is also of importance when considering that modern technology involving virtual environments is being introduced in all different sectors (e.g. military) to train humans to perform effectively, accurately and quickly. Behaviourally, the transfer of probability cueing allows us to gain insight into the potential mechanisms underlying this search process, as well as understand the flexibility or stability of the behaviour.

Chapter 5 reports three tDCS experiments that examined whether probability cueing could be manipulated under different environmental constraints: visual 2D search, virtual 3D search and full-body 3D search. Within all three of these experiments, the RPC was stimulated using anodal and cathodal parameters. The significant manipulations of probability cueing reported within this Chapter provide evidence for the role of the RPC. Finally, in Chapter 6, a general discussion of all studies will conclude, along with a comparison of behaviour across different environmental contexts. The direction of future research guided by the results from this Thesis and the practical and theoretical implications will also be discussed.

2 Methodologies for examining spatial learning

This Chapter explains the general methods used throughout this Thesis to examine spatial learning, with primary focus on virtual environments and tDCS. Each section will begin with a brief theoretical background and some important practical considerations, as well as an assessment of general strengths and weaknesses. The application of the method to this research will summarise each section.

2.1 Virtual environments

Virtual environments (hereafter, VEs) are becoming an increasingly popular tool for studying spatial cognition and learning (Bohil, Alicea, & Biocca, 2011; Dombeck & Reiser, 2012; Plank, Muller, Makeig, Onton, & Gramann, 2009; Tarr & Warren, 2002). VEs consist of a computerised, synthetic world, in which participants can visualise, interact and sometimes manipulate the environment (Bohil et al., 2011). The aim is to allow the user to *feel*, *change* and *affect* the VE as if they would in real space (Tarr & Warren, 2002). For example, visual and spatial information can be depicted as the user would normally experience it; in 3D, from a ground level and from first-person perspective (Waller, Bachmann, Hodgson, & Beall, 2007). In general, VEs are comprised of various displays that deliver stimuli or complex worlds, sensors that accurately detect user actions, and a computer that processes the sensor inputs and generates the appropriate display outputs (Kim, 2005). It is therefore often assumed that knowledge or skills that are acquired within virtual

worlds, reflect the same behaviour that occurs in the real-world, meaning that transfers of such learnt behaviours is possible (Waller, Hunt, & Knapp, 1998).

VEs consist of several technical components. Firstly, the image delivery may be in two formats: head mounted displays (hereafter, HMD) or an open display within which the image is projected onto (Bohil et al., 2011). HMDs require a computer and a head tracker that the user wears throughout the exposure time, that measures their position and orientation (Loomis, Blascovich, & Beall, 1999). The tracker accurately projects the same position and orientation of the person in virtual space. This information is then communicated to the computer which projects and renders these positions in the virtual space (Rolland & Hua, 2005). HMDs offer many advantages, including being highly immersive (Bohil et al., 2011) by allowing participants full, free mobility and head movement (Rolland & Hua, 2005). They are however, intrusive, bulky, and can sometimes weigh a lot, causing discomfort. The challenge for developers is therefore to design a light-weight, wearable HMD that also incorporates all the optics necessary for efficient immersion (Rolland & Hua, 2005). HMDs can therefore be costly to both develop and purchase (Bohil et al., 2011).

Open displays may instead be used to display VEs. These displays can consist of several large screens that are positioned together, with colour projectors displaying the computer-generated image, to create the illusion of one large space. This can be cheaper than HMDs and VEs can be made on standard computers using any software (Sharples et al., 2007). Open displays may also consist of a desktop monitor, which again, come with the ease of VE design as well as the bonus of minimal space for display. Movement within these displays tends to be controlled using computer

keyboards, a mouse or joystick controls, which may, however, offer less immersion for the participant.

Open displays may be stereoscopic or monoscopic (Mazuryk & Gervautz, 1996), meaning the VE may be viewed with, or without, the percepton of depth or 3D through binocular human vision. Stereoscopic vision is therefore very advantageous for a VE to emcompass. Stereoscopic vision is achieved in VEs by presenting the user with horizontally displaced images to both eyes, which mimics the natural disparity in visual images perceived by each eye, akin to horizontal displacement in the head (Bohil et al., 2011). These images are fused to create a sensation of 3D.

2.1.1 Considerations

2.1.1.1 Technical factors

There are several factors that should be considered when a VE is being designed including: fidelity, presence, field of view (hereafter FOV), and optic flow. These factors are not necessarily independent from each other and may interact at different levels within a VE. Fidelity is defined by the extent to which the VE and the sensory impressions and interactions are indistinguishable from the sensory impressions and interactions that the individual makes with the real world (Waller et al., 1998). Ideally, as a user interacts with the environment, they should receive the same sensory feedback as they would in the real world, such as touch and smell. More often than not, however, researchers will use either a HMD or a projected display as the only sensory input for the user (Bohil et al., 2011).

The higher the fidelity, with the most enhanced sensory input, the more likely individuals are to feel a strong sense of 'presence' (Mazuryk & Gervautz, 1996). Presence is defined as the subjective experience of being and feeling as though the user is in one place (the VE) when they are physically within another (the laboratory space) (Witmer & Singer, 1998). Presence and fidelity are linked; when both factors are increased, the behaviour learnt or exploited in the VE is more likely to reflect the real-world behaviour it is modelled on (Waller et al., 1998). This is a cost-benefit relationship though, with high fidelity and presence more likely to incur a larger financial cost. Waller et al. (1998) discuss the transfer of behaviour from VEs to the real world in terms of two types of fidelity: the environment and the interface. Environmental fidelity is defined by the degree to which the user psychological perceives variables within the VE as resembling variables that also exist in the real world. For example, a map does not have high environmental fidelity as although the distance from one landmark to another may be portrayed correctly, the route between the two landmarks may not have a high correspondence with the visual geography. Interface fidelity, on the other hand, deals with the mapping of these virtual variables to the users' mental representation of the environment. A VE would have high interface fidelity if the user was able to interact with the environment in the same way they would in the real world. For example, if a user could physically move rather than using a keyboard or joystick, this would incur high interface fidelity (Ruddle & Lessels, 2009).

Each of the human eyes has a FOV of approximately 120° vertical and 150° horizontal (Rolland & Hua, 2005). However, considering humans have binocular

vision, this means that as a pair, the eyes cover a greater FOV of 120° vertically and 200° horizontally. This FOV again expands when considering that eyes rotate 45° (meaning the FOV is 290° horizontally) and the head and body can also rotate, extending the FOV to almost 360°. In comparison, some VEs can be restrictive in their FOVs. Typically, a 21" monitor viewed from a distance of 50cm, covers a FOV of 48° whereas a HMD is slightly more improved with a FOV of between 40°-60° (Mazuryk & Gervautz, 1996). It has been suggested that a FOV of 100° or more is necessary for full immersion in virtual space (Stanney, Mourant, & Kennedy, 1998). It has also been suggested that a wide FOV (144°), with a high fidelity, incurs search patterns that almost mirror 'perfect' real world search, for example, spending more time travelling (rather than planning and standing), and making less erroneous revisits (Lessels & Ruddle, 2004). Although expanding the FOV in VEs is possible, it can come at a cost for image quality and resolution, as pixels are spread across and stretched, as well increasing participant discomfort by exaggerating feelings of simulator sickness (Rolland & Hua, 2005).

A factor closely linked to FOV is optic flow. Optic flow is the pattern of visual motion that occurs at the eye, as a person moves through space (Warren, Kay, Zosh, Duchon, & Sahuc, 2001). If a VE does not provide sufficient optic flow, then efficient user experience is reduced, having an impact on presence, immersion and learning (Stanney et al., 1998). Wider FOVs incur less restrictions on the information shown to the user during interactions with the environment, creating a larger retinal image of the environment (Ni, Bowman, & Chen, 2006). In turn, this naturally improves optic flow, as interactions can be expressed in more meaningful, realistic

ways and movement can be made at a rate that matches natural movement (Lessels & Ruddle, 2004). Enhanced optic flow and wider FOVs have been shown to facilitate navigation, spatial memory for target location, the acquisition of spatial knowledge and construction of cognitive maps (Kirschen, Kahana, Sekuler, & Burack, 2000; Lessels & Ruddle, 2004; Ni, et al., 2006; Tan, Czerwinski, & Robertson, 2003). It has also been shown that incorporating textures into a VE can enhance optic flow and target location memory (Kirschen, et al., 2000; Lessels & Ruddle, 2004), although this can sometimes be at the cost of inducing simulator sickness (Ruddle, 2004).

2.1.1.2 Participant considerations

One common occurrence during VE exposure is simulator (or 'cyber') sickness. Simulator sickness symptoms include: vomiting, eye strain, nausea, headache, increased salivation, sweating, fullness of the head, and burping (Kennedy, Lane, Berbaum, & Lilienthal, 1993). Those who suffer regularly from migraines, motion sickness or epilepsy are more susceptible to simulator sickness (Cobb, Nichols, Ramsey & Wilson, 1999; Ruddle, 2004), and it is self-reported more frequently in females than males (Biocca, 1992). Simulator sickness can be caused by a variety of factors, including the large size and heavy weight of HMDs and general individual susceptibility, however it is greatly accepted that aspects of the VE design are the most common casual effect (Ruddle, 2004). Primarily, conflicts between the sensory information that the visual and vestibular systems receives from the VE can greatly increase feelings of sickness, nausea and oculomotor strain (Kennedy et al., 1993); for example, a user may 'see themselves' moving through space but they may not 'feel' this movement. Simulator sickness can occur with all types of displays, but

participants are most likely to experience it with HMD than desktop or large screen projections (Sharples et al., 2007). Ruddle (2004) reported that users are most likely to experience symptoms when the environment is highly textured, when system latencies are present, during long periods of immersion or when movement is permitted in a downward motion to view 'virtual feet'. In comparison, large environmental dimensions, a cluttered or visually complex VE or the allowance of large rapid or uncontrollable movements, has very little effect on simulator sickness.

Cobb et al. (1999) reported that the occurrence of simulator sickness can cause large drop-out rates from VE experiments, with as many as 80% of participants reporting minor, but noticeable, symptoms, and 5% of participants experiencing effects so severe that the experiment was ceased. Simulator sickness symptoms tend to occur within the first 15 minutes of exposure to the VE, but tend to subside approximately 10 minutes after cessation of participation. The authors also found that, across studies, self-reported levels of sickness reduced upon repeated exposure, suggesting that habituation to VEs is possible.

Although the work by Cobb et al. (1999) is useful, their research is perhaps dated, using older, poorer quality VEs and hardware. Therefore, it does not consider how newer technological advances, such as reduced system lags, may have ameliorated sickness. It is currently not standard practice to report participant drop-out rates due to simulator sickness, so it is difficult to tell whether these advances have helped participant comfort. It is also important to highlight that if simulator sickness is prevalent, then the behaviours recorded in a VE may not accurately reflect the same behaviours produced in the real world. This is especially problematic when

considering that industries use VEs as training tools, to train individuals on certain tasks, before being exposed to real-world equivalents. Whether simulator sickness is classified as greatly prevalent or not, participant comfort and safety, as well as the practical implication of it, should be considered.

2.1.1.3 General advantages and disadvantages

One of the aims of VEs is to create an environment for users to interact with that is as realistic as possible. A realistic VE incurs high ecological validity, implying that the behaviour elicited within the environment, is more likely to reflect real-world behaviours and interactions (Bohil et al., 2011). VEs allow researchers to have unique control over environmental variables that can not necessarily be controlled for in the real world, such as Euclidean geometry and the laws of gravity (Waller et al., 2007). This means that researchers can understand how people respond and interact in situations when certain constraints are removed or adjusted, to gain insight into 'normal' spatial cognitive functions. Unlike the real world, researchers have precise, exact control over variables in VEs, whilst still creating worlds that are naturalistic and contextually rich (Bohil et al., 2011). It also means that variables that may have a negative effect on testing can be eradicated or reduced, such as bad weather conditions. However, it might also be considered that too much control, reduces ecological validity by producing a world less dynamic than that of the real world.

VEs allow users to practice and train on tasks that cannot easily be done so in the real world, allowing potential modification and enhancement of abilities. VEs can be designed in a flexible and personal way. For example, within the military, VEs are

used to train personnel to perform visual search efficiently (e.g. Bowen Loftin, Scerbo, McKenzie, & Catanzao, 2004), and recently this has been coupled with brain stimulation techniques to enhance these behaviours further (e.g. Nelson, McKinley, Golob, Warm, & Parasuraman, 2014). However, again, it is important to consider whether the strategies that are used in these environments are entirely reflective and representative of the same strategies used in the real world. Therefore, it is not only important to consider sample size with experimentation, but also each individual's exposure to technology and VEs.

Despite the popularity of using VEs to understand human spatial cognition (e.g. Rose, Attree, Brooks, Parslow, & Penn, 2000; Ruddle & Lessels, 2006; Ruddle, Volkova, & Bülthoff, 2011; Waller et al., 1998), VEs can be time consuming to create, depending on the software used. There is also a lack of behavioural transfer studies; it is mostly *assumed* that behaviour in virtual space uses the same mental representations and spatial mapping constructs as the real world (Waller et al., 1998). There are many factors which need to be explored, including: exposure time within the VE; level of fidelity required for efficient mapping; order of training (i.e. is it better to experience a low-risk version in the real-world environment first before training exposure in the virtual space?); what type of information is extracted during the transfer; and, the underlying cognitive processes that aid this transfer (Péruch, Belingard, & Thinus-Blanc, 2000). Of course, this is difficult to achieve when considering the sheer amount of applications and tasks that incorporate VE, and the potential for each of these to be unique in their transfer.

Another point to consider is the spatial scale and the equipment required for the user to interact with the VE. Full immersion may be difficult in VEs that are small-scale, such as when the whole environment is viewed from a single view-point (Ruddle, 2004). On the other hand, if laboratory space is restricted, this may alter how the participant interacts with the VE, in turn making it difficult to study how people learn and remember large-scale spaces. Participants may not have access to the body-based information that they would use to normally interact with the world (Waller et al., 2007). For example, a participant may be required to use a mouse or a joystick to 'move' within the VE, incurring the loss of vestibular information that they would use to navigate the real world. Distance and travel allowance may be compressed into the available dimensions of a laboratory unless treadmills are used alongside other VE hardware to assimilate movement across large-scale space. Treadmills can, however, be expensive and put participant safety at risk.

2.1.2 Summary

Over the years, VEs have developed to be effective at measuring behaviour that cannot easily be studied in the real world. VEs could be particularly useful for studying spatial learning, as diverse, contextually-rich environments can be designed, with relative ease. These environments can be made with high ecological validity, control and precision.

Thus far, there have been no experiments that have examined probability cueing in a virtual context, although it is a methodological opportunity that has been suggested (e.g. Jiang et al., 2014). It is important to study probability cueing within

VEs, as learning in this context may provide further evidence of the mechanisms involved in this search process. From previous literature, it is clear that probability cueing in visual search (Geng & Behrmann, 2002) may operate differently to probability cueing in real space (Smith et al., 2010), because participants report knowledge of the cue in the real world, and do not under visual search constraints. As mentioned previously, VEs are also being used as tools to train individuals to perform efficiently on tasks. The experiments detailed later in this Thesis that use VEs, all bear this underlying assumption in mind, considering the initial knowledge acquisition and later transfer of behaviour across environments. The next sections describe the VEs that are used in the experiments in this Thesis.

2.1.3 VEs in the current research

Probability cueing in VEs is examined in Chapter 3 (Experiment 1 and 2), Chapter 4 (Experiment 4) and Chapter 5 (Experiment 6). This next section covers the creation of the search arrays, the appearance of the VE and the methods employed to monitor symptoms of simulator sickness and reduce their occurrence. These factors were kept constant throughout all experiments, unless stated otherwise. More detailed explanations of each VE, including the trial design and display set-up, will be provided within the respective chapter.

2.1.3.1 Array creation

Within all experiments, 12 search items were presented on each trial, at ground level, and within a constrained virtual arena. These items were positioned in a way so that an even amount of space was covered. A series of randomising

procedures were undertaken to create multiple search arrays. Each participant viewed a different combination of search locations and trial sequences, although the graphics of the VE stayed constant across the group.

Firstly, a series of six arrays were created using 3x3 grids. Three search locations appeared in each grid and each location appeared in one row and one column only. After six arrays were created, each was randomly assigned a quadrant number from one to four. This procedure was completed 20 times to create 20 different combinations of arrays in the four quadrants for each of the 20 participants in each experiment (apart from Experiment 6). The four quadrants then created a larger 6x6 grid consisting of 12 search locations overall. **Figure 2.1** illustrates this.

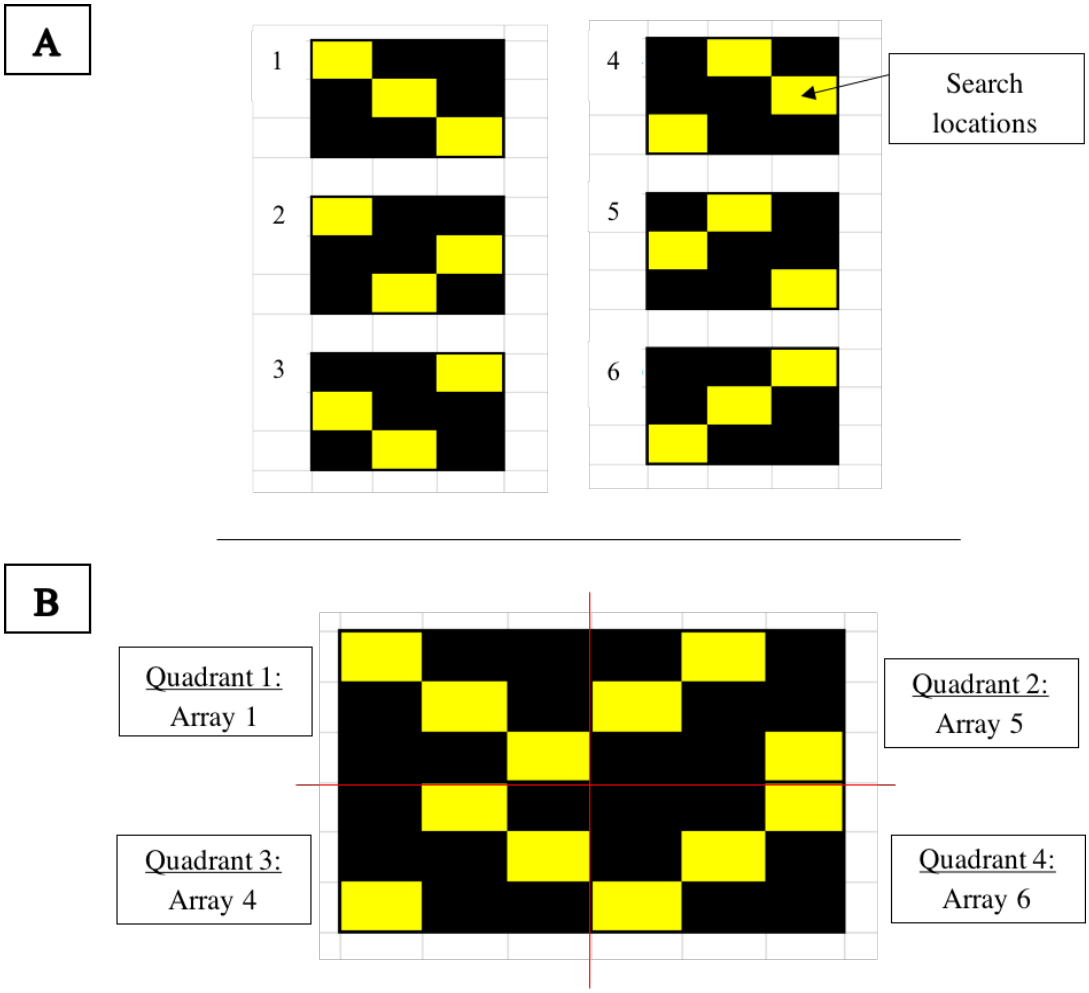


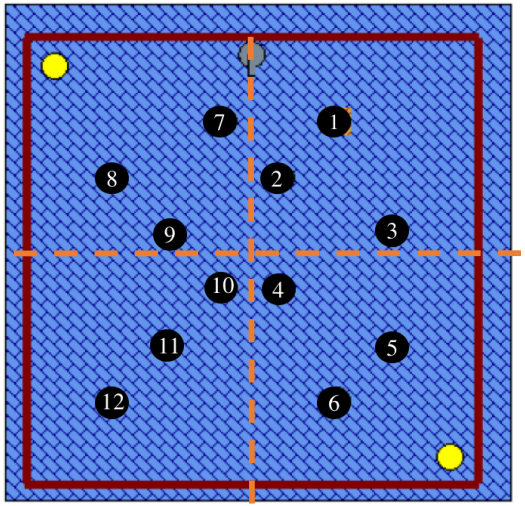
Figure 2.1: **A**: Six arrays created in Microsoft Excel using a basic rule: each search location appeared in one row and one column only. **B**: Arrays randomly combined into 4 quadrants to create a larger 6x6 grid with 12 search locations overall. This was conducted 20 times.

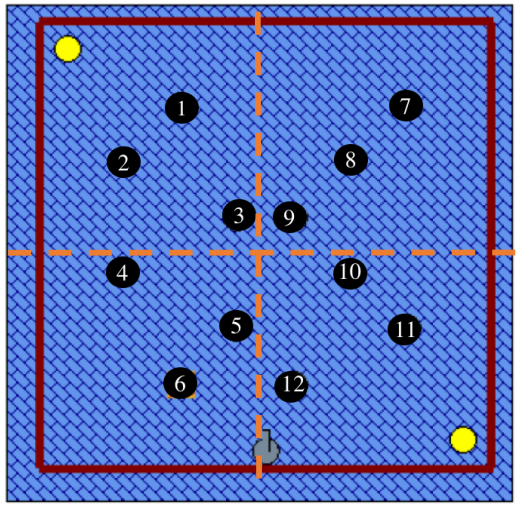
2.1.3.2 Start position and trial probability

Participants began their search at the edge of the array, along a central axis, oriented sagittally, in relation to the probability distribution. Participants could start at either end of this axis (north and south, respectively). After the array combinations were designed, the counterbalancing of start position and display probabilities were designed, followed by the visual design of the environment.

The 20 combinations were firstly split into groups of five. Within the VE, the participants either started from the north of the environment (start position one) or south (start position two). The cued side and uncued side were egocentrically defined according to the midline point that the start position was centred on. Five combinations starting at position one, and five combinations starting at position two, were defined by the target appearing 80% on the right side of the display (cued side) and 20% on the left side (uncued side). The cued and uncued side were reversed for the other 10 combinations for start position one and two (five combinations of each, respectively). Therefore, the target could also appear 80% of the time on the left side of the display (cued side) and 20% on the right side (uncued side).

Table 2.1 Randomising trial procedure demonstrating how target locations inform the cued and uncued sides of the display. Start positions are represented in the MazeSuite diagrams as grey circles; target locations are numbered; lights are represented by yellow circle. Dashed lines represent the invisible quadrant.

Start position	Environment plan view	Egocentric cued side (80%)	Possible target location	Egocentric uncued side (20%)	Possible target location
1 – North		Left	1, 2, 3, 4, 5, 6	Right	7, 8, 9, 10, 11, 12
		Right	7, 8, 9, 10, 11, 12	Left	1, 2, 3, 4, 5, 6

2 - South		Left	7, 8, 9, 10, 11, 12	Right	1, 2, 3, 4, 5, 6
		Right	1, 2, 3, 4, 5, 6	Left	7, 8, 9, 10, 11, 12

2.1.3.3 VE visual appearance

Following array creation, a VE was created using MazeMaker computer software, part of the MazeSuite package (Ayaz, Allen, Platek, & Onaral, 2008; *www.mazesuite.com*). The VE was a square arena viewed from a first-person perspective, with two distinct walls; **Figure 2.2** demonstrates the environment from the participants' view. Assuming a walking speed similar to that of the real-world of 2m/s, each of the four walls was approximately 6m in length and 2.5m in height. There was no ceiling to the arena, meaning that any space above the top of the walls appeared a solid black colour. In Experiments 1, 4 and 6, the four walls were textured to brick or fence although both joined together in the middle to create one solid wall. The grass ('ground020.jpg'), brick ('brick.jpg') and fence ('wood2.jpg') textures were all retrieved from the MazeSuite standard library and were set to 'tile' onto the walls. In comparison, in Experiment 2, the four walls were solid colour with either yellow (RGB: 255, 255, 0) or blue (RGB: 0, 0, 255) with a grey (RGB: 178, 178, 178) colour floor. The reason for these differences is outlined in the respective chapters.

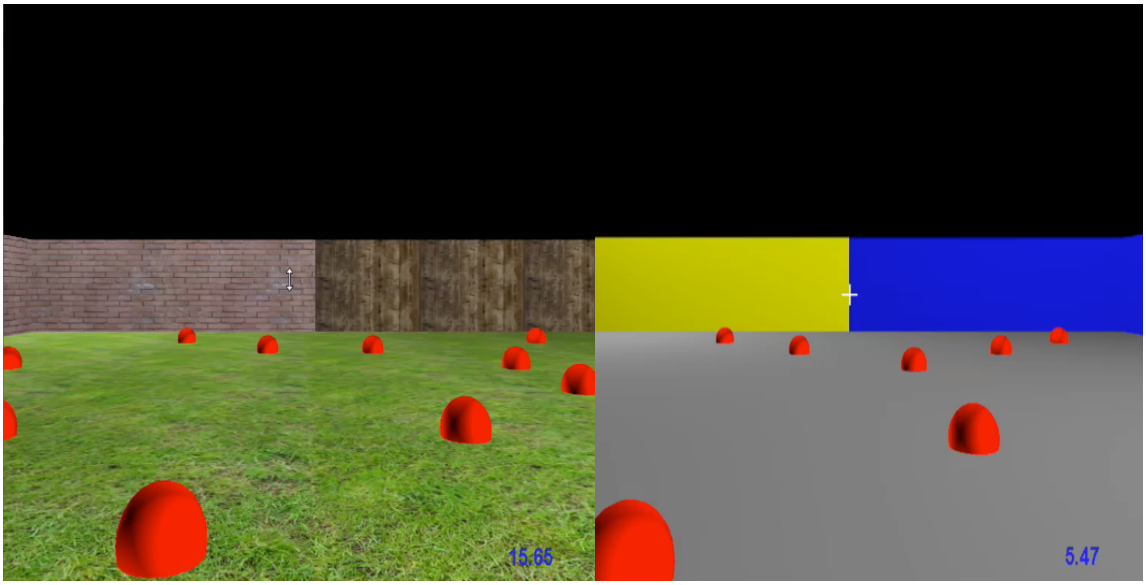


Figure 2.2 VE viewed from the start position. *Left:* VE used in Experiments 1, 4 and 6; *right:* VE used in Experiment 2.

Throughout all experiments, 12 red hemispherical items representing the search locations were displayed on the floor of the environment. These items were created from the standard MazeSuite library, using the model named 'sphere red.obj'. Each object was programmed so that collision was 'false', meaning that movement could be directed over the top or through the objects. As mentioned previously, the environment was divided into four invisible quadrants, with three items in each, to ensure an even amount of space was covered. Participants were not told of this and the quadrants were not visible to them. No items were located on the midline point. The items were in a slightly smaller square arena of 4mx4m to allow the participant to view all items easily from the start position (although their FOV was still limited). The array, the cued and uncued sides and the start position remained fixed throughout the experiment as a previous study suggested that these properties are needed to align

the reference frames and encourage probability cueing in 3D contexts (Smith et al., 2010).

For each combination, 12 'region' files were created. Within each of these files, the combination of the search items was the same and, visually, the environment was identical, but the end region differed (i.e. the target was located under each of the 12 items). Once these 12 files had been created, the trials were created using the 'MazeList Builder' function in MazeMaker, according to the trial order which was created by a randomising procedure. The trial order is explained in each respective experiment. The trial number differed across experiments: Experiment 1, 4 and 6 include 60 trials, whereas Experiment 2 uses 30 only. Participants completed trials in blocks of 30; when 60 trials were used, these were split into two blocks of 30 trials. During the experiment, the MazeList Builder file was uploaded to MazeWalker, which displayed the trials in the order as specified in the list.

2.1.3.4 Deriving spatial learning measures

The four measures that were derived from the VE experiments were: search time, first visits, density and number of visits. Definitions of these measures are detailed in **Section 2.3**. The measures were extracted by firstly using MazeAnalyzer software (Ayaz et al., 2008).

Firstly, a region file was uploaded into the software (see **Figure 2.3**). The data that matched the combination shown in this region file was then superimposed on top of the region file. Regions of interest were then defined for each search item (12 in total), and named according to the potential target label assigned during the creation

of the combinations (see **Table 2.1** for an example of the search item location labelling). The regions of interest were defined using the X and Y coordinates of each search item in MazeBuilder. The 'measure' function then extracted: the search item label, the time that item was "entered" and "exited", the distance that had been travelled when the item was "entered" and "exited", and how many times the item had been visited. Enter/exits were recorded according to the borders of the region of interest.

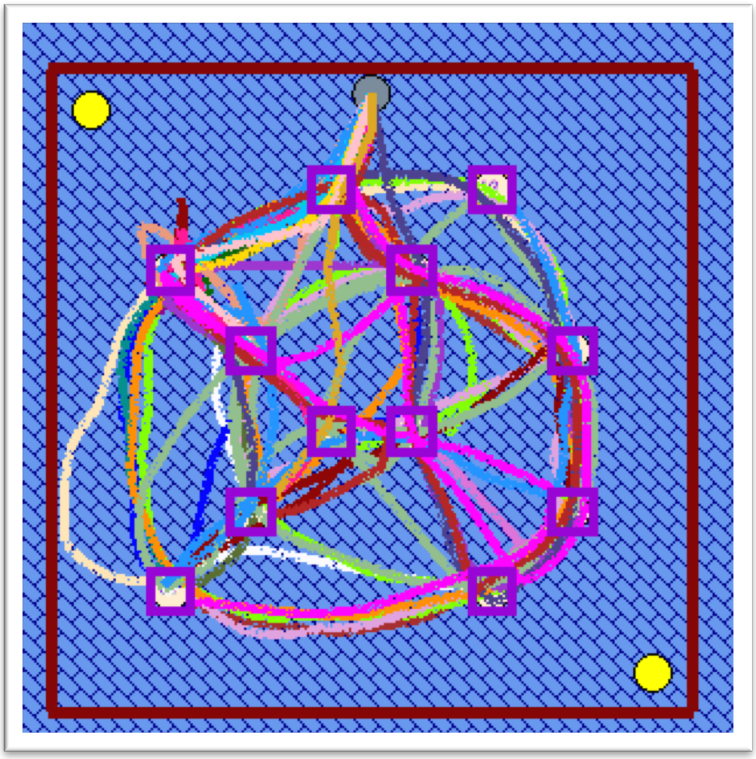


Figure 2.3 MazeAnalyzer software showing a region file, with all data from 30 trials and the regions of interest (purple boxes) superimposed on the file.

Following this, the file was saved and the relevant information (search item label, entered timestamp) was extracted using a LabVIEW programme. The trial

number and the order of each visit to the search items within that specific trial was also added to the file. The data was then entered in an Excel spreadsheet, specially designed to extract the measurements for each of the combinations. This spreadsheet produced the data for the final four measurements, which were then entered in SPSS for analysis for each participant.

2.1.3.5 Monitoring simulator sickness

Simulator sickness was monitored using the Simulator Sickness Questionnaire (SSQ - Kennedy et al., 1993) during Experiment 2, as a large open display was used. This self-report questionnaire includes several symptoms that the user rates from 'none' to 'moderate' to 'severe'. The SSQ has high reliability and internal consistency (Bouchard, Robillard, & Renaud, 2007). It was given to participants throughout the course of Experiment 2, to monitor side effects and to identify potential withdrawals if any symptoms were rated as severe. This is detailed more in **Section 3.4**.

Participant comfort and safety was paramount to all experiments. Participants were regularly asked whether they were experiencing any signs of sickness. If at any point the participant reported severe discomfort, they were advised to remain calm and relaxed, try to stay still and maintain gaze on a fixed point, leave the laboratory if they wished to get some fresh air and have something to eat or drink. Water was available at all times, and throughout each experiment the laboratory was maintained at a cool temperature (between 18-20°) by an air conditioner, as well as a fan blowing cool air in front of them (applicable to Experiment 2 only). Furthermore, Stanney and Kennedy (2009) outline several 'red flags' that can help Experimenters

to determine whether a participant is feeling simulator sick, without necessarily truthfully reporting their symptoms. These include: looking away from the screen or shifting attention into the corners of the screen or floor; squinting or closing one's eyes; changing sitting, body or head position regularly and fidgeting; deliberately controlling breathing or calming one's heart rate by taking shallow breaths. During each VE experiment, the participant was observed closely and was advised to stop if any of these symptoms were adopted.

2.2 tDCS

As explained in Chapter 1, tDCS is a brain stimulation technique that modulates action potentials in a polarity-specific manner. The mechanisms of tDCS action are explained in **Section 1.2.2.1**. tDCS uses a battery-powered machine that emits a weak direct electrical current, traditionally via the placement of two electrodes placed on the scalp of a participant (Nitsche et al., 2008). One electrode is known as the active electrode and the other a reference electrode (Bikson, Datta, Rahman, & Scatturo, 2010), although both have a current flowing through during stimulation to complete the electrical circuit. The active electrode is positioned to overlie a region of cortex which is thought to be relevant to the behaviour of interest. In comparison, the reference electrode tends to be positioned in an area which is thought to have little involvement in the task. This is explained in more detail in **Section 2.2.2.1.**

Lippold and Redfearn (1964) were one of the first researchers to indicate that a transcranial current of 0.5mA could change the mood of human participants. They were also the first experimenters to use a model equivalent to modern tDCS, with

electrodes positioned on the head in an extracranial manner, rather than intracranial. However, it was not until approximately 20 years ago from the present day that modern tDCS research emerged via a seminal paper by Nitsche and Paulus (2000), indicating that the motor cortex could be reliably targeted using weak electrical currents. Since then, researchers at the University of Gottingen have, arguably, remained at the forefront of tDCS research, popularising, developing and investigating the method. Popularity of the technique has grown over the past decade, as exemplified in a PubMed search, returning 2227 published articles containing the phrase 'transcranial direct current stimulation' between 2013 and 2017, in comparison to 712 articles published between 2007 and 2012 (July 2017).

Although the mechanisms of action of tDCS are unclear, one of the original aims was to examine its effectiveness as a treatment for psychiatric and neurological conditions (Coffman et al. 2013; Nitsche et al., 2008). In the future, it is thought that tDCS may be used alongside drug treatments, or even as a substitutive treatment, to speed recovery and improve daily motor and cognitive performance (Brunoni et al, 2012). This is especially important for low or middle income countries where cheap, effective treatments may be necessary (Brunoni et al., 2012; Fregni et al., 2005).

Aside from clinical applications, tDCS is increasingly being used on healthy populations to temporarily modify behaviour, accelerate learning and boost human performance on cognitive and motor tasks that may normally take a while to master (Coffman et al., 2013; Parasuraman & McKinley, 2014). Examples include significant tDCS effects reported during visual search tasks, working memory tasks and attentional tasks (for a review see: Coffman et al., 2014). Alternatively, tDCS may be

used as a non-invasive application for understanding brain function during and after cognitive and motor training processes (Filmer, Dux & Mattingley, 2014). A change in performance during or after a brain area has been stimulated may indicate the importance of that region for a specific behaviour. In comparison, if no change is demonstrated, this may indicate that that brain area plays a minimal role in the measured behavioural outcome.

2.2.1 Considerations

2.2.1.1 Methodological considerations

There are three types of experimental groups to consider for tDCS: anodal, cathodal and sham. In all experimental groups, the programmed current is slowly ramped-up to full, active stimulation over the course of 10-30s. For the active stimulation groups (anodal and cathodal), this ramp up is then followed by a period of time in which the stimulation is emitted at full current. Full current tends to be between 0.5mA-2mA, with 2mA being the cut-off point for safety and comfort in human experimentation (Iyer et al., 2005). This period of time is programmed by the experimenter, and generally ranges from 5-30 minutes (Bikson, Datta, & Elwassif, 2009). Once the period of active stimulation is complete, the current is slowly ramped-down, again over the course of a few seconds. The ramping-up/-down of the current helps to avoid uncomfortable 'startle-like' effects (Nitsche et al., 2008).

Sham tDCS provides a control condition, in which the current is slowly ramped-up to active stimulation level, followed by a very short burst of stimulation (~30s). The current is then ramped-down, rather than staying active. The participant

continues to wear the electrodes for the same amount of time as the active stimulation groups. The short burst of stimulation does not modify cortical activity (Nitsche et al., 2008), but instead replicates the same cutaneous sensations (e.g. itching, tingling) that are reported within the first few seconds of active stimulation (Gandiga, Hummel, & Cohen, 2006). In general, sham tDCS is regarded as an effective blinding technique especially for those who have never experienced it before (Ambrus et al., 2012; Gandiga et al., 2006). However, for people familiar with tDCS, effective blinding is difficult and may not be achievable (Ambrus et al., 2012).

Both within- and between-subject designs can be used to examine tDCS effects. A within-subject design involves exposing the same sub-set of participants to all experimental conditions – in this case, all would participate in cathodal, anodal and sham stimulation conditions. For between-subject designs, more participants are tested and each participant is only exposed to one experimental condition, such as anodal.

Within- and between- subject designs both have their own pitfalls associated with current flow, current direction, and responsiveness. For example, it has been shown that an individual's unique anatomy (e.g. skull thickness) can influence the current (Datta, Truong, Minhas, Parra, & Bikson, 2012; Li, Uehara, & Hanakawa, 2015; Opitz, Paulus, Will, Antunes, & Thielscher, 2015). Within-subject designs therefore minimise this, as participants experience multiple stimulation conditions – although this may itself lead to the negative consequence of subject attrition. It is also advisable to ensure that participants return at the same time on all testing days to reduce the risk of circadian influences (Krause & Kadosh, 2014; Li et al., 2015).

Much more recent research has also suggested that intra-individual differences play a strong role in current action (Dyke, Kim, Jackson, & Jackson, 2016) and, irrespective of experimental design, these are difficult to overcome. There are also currently no standardised guidelines that provide the length of time that should be left between stimulation sessions, with some studies suggesting that stimulation over consecutive days can cause sizeable unwanted (and, potentially, unsafe) cumulative effects (Alonzo, Brassil, Taylor, Martin, & Loo, 2012). It has been advised that at least a week between testing sessions allows the effects to 'wash out' (Boggio et al., 2007) unless a cumulative modulatory effect is desired, such as in the case of testing clinical populations.

In contrast to within-subject designs, between-subject designs require recruitment of large cohorts to ensure that effect sizes are reliable. As individual anatomies cannot be controlled for in this type of design, tDCS intervention becomes a between-subject factor in any analysis, meaning that designs are more vulnerable to these interindividual effects (Berryhill, Peterson, Jones, & Stephens, 2014). However, MRI-guided electrode placement may reduce this slightly, by ensuring that the exact brain region of interest is targeted for each individual. Between-subject designs also reduce the risk of practice or learning effects across testing sessions, rather than enhance them, as is the case with within-subject designs.

2.2.1.2 tDCS parameters

Electrode positioning is an important experimental parameter for any tDCS design. In a traditional tDCS set-up, two electrodes are attached to the scalp using

rubber bands or caps. Both may be attached to the scalp (cephalic electrodes); one corresponding to the targeted brain region of interest for active stimulation, the other used as a reference (Nitsche et al., 2008). Alternatively, one electrode may be attached to the region of interest on the scalp whilst the other may be attached extra-cephalically, to a region on the body outside of the scalp (Bikson et al., 2010). It is important to note that although the target electrode may emit an anodal current, for example, the reference electrode also emits a cathodal current at the same time. Electrode positioning is important for tDCS studies, as electrode placement determines current flow. For example, using brain modelling techniques, Bikson et al. (2010) found that when the active electrode was placed over the motor cortex and the reference electrode was placed over the forehead, current flow was directed over the frontal lobe. Alternatively, when the active electrode was positioned in the same place and the reference electrode was placed extra-cephalically (on the mastoid, behind the ear) current flow was directed down the posterior regions of the brain and through the brain stem.

As well as electrode positioning, electrode size is also important for tDCS experiments. The most commonly used electrode sizes[1] are between 5x5cm and 7x5cm (Utz, Dimova, Oppenländer, & Kerkhoff, 2010); the suitability of dimensions can depend on the stimulation site. They also depend on current density calculations: the quotient of stimulation intensity (mA) and electrode size (cm^2). Current density can be calculated to determine the approximate electrical field strength, thought to be

[1] However, see Villamar et al., 2013 for a guide on HD-tDCS, that instead uses four small electrodes ('ring' electrodes) surrounding one active electrode. It is thought that HD-tDCS may enhance spatial focality of tDCS, but at the potential cost of participant comfort.

injected into the tissue below the electrode pad (Nitsche et al., 2008). It has been suggested that current densities should be above a threshold of 0.017mA/cm^2 to actively stimulate the cortical regions below the electrode pad (Nitsche & Paulus, 2000). These calculations are especially important when researchers use the same electrode size for active and reference electrodes; this ultimately means that the same current density is emitted to different brain regions, across both electrodes, making polarity-specific conclusions difficult to draw. It may therefore be important to use two different size electrodes to allow for more accurate conclusions to be drawn.

2.2.1.3 Participant considerations

There are no standardised published guidelines on the safety thresholds for the use of tDCS. There are, however, some studies that have examined the safety of tDCS (e.g. Brunoni et al., 2012; Poreisz, Boros, Antal, & Paulus, 2007). Various safety reviews (e.g. Arul-Anandam, Loo, & Sachdev, 2009; Poreisz et al., 2007) have reported no serious adverse effects related to tDCS when using similar stimulation parameters to the ones used in this research; this is detailed and discussed further in **Chapter 5**. However, mild and temporary side effects may occur such as headache, a cutaneous sensation and redness of skin under the electrode pad, moderate fatigue, trouble concentrating, acute mood changes and temporary nausea. These effects are self-reported within a small percentage of individuals (approximately 17%), but the intensity of tingling and itching is more frequently reported in healthy subjects than patients, of whom in comparison report more headaches (Poreisz et al., 2007). Side effects are temporary and tend to reside as soon as tDCS is stopped (Nitsche et al., 2008). It is important to consider that not all symptoms may be associated with tDCS

directly, such as moderate fatigue, that may instead be related to participation in an experiment.

It is currently not standard practice to report side effects, nor to monitor them during stimulation. Some research groups supply participants with self-report side effect and mood questionnaires (e.g. Coffman et al., 2012) but, again, this is neither standardised nor common. All experiments that use tDCS in this Thesis required participants to rate how they felt using a scale for tDCS-related side effects and pseudo items, before and after stimulation. The 'before' measure allowed the Experimenter to use their discretion to not commence tDCS, as some symptoms may be exuberated during stimulation, such as eczema (Loo et al., 2011). This helps minimise the risk of the development or extension of side effects to the participant. The 'after' measure also allowed the Experimenter to monitor the participant post-stimulation if necessary. This Safety Questionnaire, along with instructions on its use, is detailed in **Appendix 1**.

There is currently no standard or established exclusion criteria that should be adhered too. However, there are some commonalities across studies, of which the exclusion criteria for the tDCS experiments in this Thesis are built upon. These criteria are detailed in **Section 5.2**. If a participant adhered to any such criterion, they were automatically excluded for their own health and safety. All participants were also screened using a Screening Questionnaire (**Appendix 2**), to assess their individual risk of participation and stop recruitment as required.

2.2.1.4 General advantages and disadvantages

tDCS offers many advantages including its mobility, portability and its ease of set-up. Unlike other brain stimulation methods, tDCS consists of a small, portable box and long electrode cables. This means the device is mobile and can be used with a whole range of experimental designs and methodologies, including brain imaging techniques such as functional near infrared spectroscopy (McKendrick, Parasuraman, & Ayaz, 2015). The tDCS equipment is also reusable, inexpensive and if damaged or worn, easily replaced. The machine utilises one or two standard batteries (for safety reasons), which can last for weeks or months, depending upon how often it is used. Stimulation programmes are also relatively easy for researchers or even patients to self-administer.

As highlighted in the previous section, there are many parameters to consider when designing a tDCS experiment. One issue that has recently been highlighted within tDCS research is the lack of standardised methodologies, parameters and electrode montages (Horvath, Carter, & Forte, 2014). This lack of standardisation makes it difficult to design experiments using tDCS, as its effects may be very difficult to directionally predict. It has also been recently shown that cognitive tDCS studies are particularly susceptible to finding facilitatory effects of cathodal stimulation, rather than anodal stimulation (Jacobson et al., 2012). On the other hand, it has been suggested that cathodal stimulation has no effect on cognitive functions (Filmer et al. 2014), nor does a single session of tDCS, no matter what type of stimulation a participant receives (Horvath, Forte, & Carter, 2015). Collectively, these findings demonstrate that the polarity-specific effects of anodal and cathodal may not

be as predictable as assumed, and may be due to the lack of standardised set-ups and experimental protocols within in the literature (Li et al., 2015). They also emphasise the importance of including all three types of experimental groups (anodal, cathodal and sham) within an experimental design, to test the unpredictable nature of different types of tDCS.

There are also factors that should be considered when analysing data and drawing conclusions from results. Firstly, more research is needed to decipher the underlying mechanisms of tDCS effects on the cortex. These mechanisms are currently poorly understood, making it difficult to predict responses as well as explain some results (Berryhill et al., 2014). Secondly, it has been demonstrated that networks of functionally-connected regions to the stimulated region may be recruited during tDCS (e.g. Ellison et al., 2014). This focality issue should be considered when linking a specific process to an area of cortex (Filmer et al., 2014). Finally, it should be remembered that both intra- and inter-individual differences exist. Averaging data may mask these individual effects and as such, some researchers have now started to report individual participant data (e.g. Nitsche & Paulus, 2001).

2.2.2 Summary

Although tDCS is a relatively novel neurostimulatory technique, it has received a great deal of research attention. As research progresses, more factors that affect current control, flow and direction are bound to surface, as well as standardised safety guidelines. There are many parameters to consider when designing a tDCS experiment, ranging from electrode size to the experimental design. Sometimes

parameters are chosen based on successful results in previous tDCS experiments. The most important parameters for a tDCS experiment were discussed in **Section 2.2.2.1**. Justification and details of the chosen stimulatory parameters in the tDCS experiments discussed in this Thesis, are detailed **Section 5.2**.

As detailed in **Section 1.2.1**, tDCS has been used to modify visual search behaviours in healthy populations (e.g. Ball et al., 2013). It has also been used to investigate the induction of hemifield biases, and as well as the amelioration of these effects in hemispatial neglect patients (e.g. Sparing et al., 2009). As of yet, however, there have been no systematic attempts to use tDCS to modulate probability cueing. If a change is observed after or during stimulation to the RPC, this could indicate that this region is important for efficiency of search or accuracy of learning – a brain-behaviour relationship could be unveiled. This will be examined in Chapter 5, in which tDCS was applied to probability cueing tasks designed within: a visual search context (Experiment 5), a VE search context (Experiment 6), and a full-body search context (Experiment 7).

2.3 Measuring spatial learning

Based on previous experiments (e.g. Buckley & Smith 2013; Pellicano et al., 2011; Smith et al., 2010), four dependent variables were chosen as a means of measuring sensitivity to probability cueing and learning. These variables were:

⇒ **Search time**: Median time (seconds) to find the target (comparing cued and uncued trials).

⇒ **First visits**: The first search item visited across trials, expressed as a percentage of first visits directed towards search items on the cued side of space.

⇒ **Density**: The relative number of visits made to search items on the cued side of space. Again, this is expressed as a percentage.

⇒ **Number of visits**: The mean number of visits to search items (comparing cued and uncued trials).

Traditionally, probability cueing has been measured using RT in visual search tasks (e.g. Geng & Berhmann, 2002). Search time has also been used to measure probability cueing in large-scale search paradigms (Smith et al., 2010), hence this measure provides a basic means to compare one condition to another in a manner that is consistent with previous demonstrations of probability cueing. The median search time was used as it is a more robust measure to analysing timed data than the mean (Whelan, 2008). Compared to the mean, the median may be less influenced to slow and fast outliers and positive skew in datasets (Ulrich & Miller, 1994) – a common occurrence in datasets that record time, where a below zero value is unobtainable (Whelan, 2008). Furthermore, as the amount of trials contributing to cued and uncued trial types is largely uneven and small in size (because of the statistical regularities of the search array), the mean is more likely to be skewed by this than the median, where the mid-point per trial type is recorded; see Van Selst and Jolicoeur, (1994) for an example of this using the Posner cueing task.

An important point to highlight here is that the above measures were used to assess probability cueing in all studies, apart from Experiment 5. In this experiment, the effects of tDCS on probability cueing in a visual search task were examined. RT (milliseconds) was the primary measure of efficient probability cueing. Although both RT and search time are measurements of time, they operate on different timescales. Search time involves more planning and a slower decision making process in comparison to RT (Jiang et al., 2016). For example, when navigating a VE, participants may look around the environment for a few seconds (planning stage) before moving towards a search item (movement, decision stage). This planning and movement takes several seconds to complete. In comparison, visual search may involve little planning, and instead a quick scan of an array, with a quick decision to follow. Eye movements are 'cheap' and easy for individuals to make, whereas movement and foraging search through virtual or real space instead involves a more effortful search with higher-order decision making (Jiang et al., 2016). RT is therefore measured in smaller units (ms) as time to find the target is a lot quicker than search time (s).

Another factor to consider is that, unlike RT guided by eye movements, search time can be confounded by a variety of factors, such as path length and movement speed. First visits, density and the number of visits are not confounded by such factors, are independent of individual differences in the speed of task completion (Smith et al., 2010) and have been used in previous large-scale probability cueing experiments as measures of sensitivity of probability cueing (e.g. Pellicano; Smith et al., 2010). The number of visits is arguably the equivalent of fixations during a visual

search task – the movement from one search location to the next. This basic measure of search efficiency can be compared between cued and uncued trials and is not confounded by other properties of search movement. However, the number of visits does not capture bias in the participants search behaviour, as it is a measure of an averaged cumulative total between the two conditions. Density, on the other hand, measures preference, as it disregards the number of visits (which may sometimes be high, or sometimes low, regardless of the trial type), and instead is a percentage of whether there is bias towards one side, over the entirety of the trial. It also is independent of speed; hence this measure of search bias may be the most sensitive at capturing probability cueing.

Finally, first visits capture an initial decision-making process. During search, one might consistently be drawn to a nearby location, even if it is on the uncued side. This may be because of its proximity or because of the strategy the participant choses; it may be the easiest location to reach on their search path. Demonstrations of bias can be dynamic over the course of any given trial, as participants may adapt their search paths based on previous inspections. However, the first visit is not subject to interference from any previous inspection and therefore can be considered a measure of preference for one side over the other – the equivalent of a two-alternative forced choice.

2.4 VEs, tDCS and spatial learning

This chapter has outlined two methodologies that will be used in this Thesis (VEs and tDCS), as well as the measurements that will be used to examine spatial

learning across all experiments. Respective methodologies will be discussed in more detail in each corresponding experimental chapter:

⇒ Chapter 3: Experiment 1 and 2 examines probability cueing in the VE.

⇒ Chapter 4: Experiment 4 examines the transfer of probability cueing from a VE to a laboratory space.

⇒ Chapter 5: Experiment 5, 6 and 7 use tDCS to examine the effects of anodal and cathodal stimulation on probability cueing. Experiment 6 examines the tDCS effects of probability cueing in a VE.

3 Probability cueing in virtual and laboratory space

3.1 Introduction

Over the course of time, visual search behaviour can become biased and reflect some form of sensitivity towards the spatial statistics of target distributions. Geng and Berhmann (2002) found that when a target appeared with greater likelihood in one half of a search array, participants became faster at locating it, in comparison to when the target was located on the other low-probability side. However, participants, did not report awareness of the uneven distribution when probed after the task, suggesting that probability cueing operates below a level of conscious awareness. In contrast, studies that have employed large-scale search paradigms (e.g. Smith et al., 2010), in which full body movements are required to inspect locations, report that probability cueing is more complex, requiring a combination of stable spatial cues and, when successful, it appears that participants have awareness of the cued side.

It has been argued that visual search exploits the same mechanisms as 'real world' naturalistic search (Klein & MacInnes, 1999; Thomas et al., 2006; Wolfe, 1994). For example, Thomas et al. (2006) designed an experiment to examine whether inhibition of return - a process that is well-established in visual search - could be generalised to the virtual domain. Inhibition of return is defined as the suppression of return to a previously, attended, recently inspected location (Klein & MacInnes, 1999). Using a HMD VE task, Thomas et al. (2006) asked participants to find a hidden piece of fruit amongst an array of leaves. After searching under several leaves,

one leaf would flicker to indicate that the fruit was below it – this leaf would either be one that the participant had already visited or one that they had not yet inspected. Participants were slower at selecting the leaf that already had been inspected. Although RTs were much longer in the virtual space in comparison to visual search, inhibition of return was still found. The authors concluded that this study provided evidence that inhibition of return is domain-general, insofar as it can be demonstrated in visual search and search conducted in representational space.

Although this study provides evidence for a domain-general mechanism, there are very clear differences between search that is conducted under pure visual constraints and within a large-scale real-world context. It is also clear from the probability cueing literature that visual search tasks and large-scale laboratory search tasks both operate differently in terms of conscious awareness of the cue. There are clear methodological differences and demands between the two types of tasks that may account for these behavioural discrepancies (see **Table 1.1.** for further details). For example, actively searching a real-world environment requires full-body movement and associated physical effort, in turn incurring active updating of spatial reference frames (Jiang et al., 2014; Smith et al., 2010). Visual search, on the other hand, requires eye movements only. Furthermore, the distance between search items may be far greater in real world search in comparison to visual search (Jiang et al., 2014). Items may be presented within close range on a computer screen, whereas in large-scale search, items may be occluded and not within reaching distance. This also emphasises the response differences between visual search and large-scale search.

Visual search tends to require a singular response, commonly a button press, to signify the presence or absence of a target item. RT and accuracy measures are then recorded. In comparison, large-scale, foraging search requires a greater decision and planning process as an individual must decide where to direct their efforts whilst accounting for time and energy expenditure (Smith et al., 2010). For example, the Marginal Value Theorem of Foraging (Charnov, 1976) suggests that individuals make decisions regarding which areas to visit and when it is economically favourable to leave the area and move onto the next for further food resources. Thus, if the wrong judgements are made, individuals lose time travelling to and from locations, as well as energy through locomotion during the travelling. Memory may also play a more prominent role in large-scale, foraging search than visual search, as revisiting areas is not only costly to time, but also effort (Gilchrist et al., 2001). Studies have shown that adults (Smith, Hood, & Gilchrist, 2008) and typically developing children (Pellicano et al., 2011; Smith, Gilchrist, Hood, & Karmiloff-Smith, 2006) produce fewer revisits in large-scale space than in visual search (Gilchrist et al., 2001), suggesting that memory is used more frequently and tracking items may be more useful in a larger environment. Overall the process involved in large-scale search is more taxing in comparison to visual search, with physical effort and movement as a necessary requirement.

Although there has been an abundance of studies examining the role of probability cueing in visual search, there are few published experiments that have incorporated the requirement of full-body movement. To date, there have been two studies that have examined probability cueing in a large-scale context, both with

slightly different conclusions. Smith et al. (2010) found that successful probability cueing was reliant upon invariable spatial reference frames. A stable array and start position were important factors that supported learning of the cue. Participants also reported conscious awareness of the probability cue, unlike under visual search constraints. In comparison, Jiang et al. (2014) found that probability cueing in a large-scale context operated below conscious level and could occur even when reference frames were disassociated. Arguably, the task designed by Jiang and colleagues was analogous to visual search rather than large-scale search, as participants remained static and had to use eye movements to find the target. This may account for these differences in results.

Together, the findings from visual search and large-scale search studies show clear differences between spatial learning across the two environmental contexts, despite some researchers arguing for visual search as a domain-general mechanism (Klein & MacInnes, 1999; Thomas et al., 2006; Wolfe, 1994). One approach to understanding whether these two search processes use the same mechanisms is to examine probability cueing under a context that is a medium between the two. One such medium is VEs.

Exploring probability cueing in a VE offers many practical advantages, including the ease of construction of a highly-controlled world that allows naturalistic search behaviour to be simulated (Tarr & Warren, 2002), in minimal laboratory space. VEs allow search to be studied in 3D space, with the maintenance of an egocentric viewpoint; two factors that are reflective of foraging in real space. On the other hand, features that may affect search negatively in the real-world such as the viewing height

of a participant and their physical ability, can be controlled for, again with ease. Reducing physical effort also allows for a greater number of trials to be used and a reduction in the total experiment length. Furthermore, most virtual reality software, such as the one used in the following experiments, enables many spatial learning measures to be extracted. Extracting these measures allows search processes that have been deduced from VEs, just like real space, to be examined in intricate detail.

Although the aforementioned points highlight the usefulness and strengths of VEs to studying search processes, it is important to consider that the removal of locomotion cues and physical effort may affect search. VEs that use hardware such as joysticks and keyboards allow the user to move in virtual space, but remove the physical effort and movement required under real world constraints. HMDs can be paired with treadmills to permit movement, or alternatively laboratory space may be large enough to allow the individual to move within large virtual spaces. It is unknown whether removing locomotion cues whilst in an environment that exploits some features similar to real-world space, influences probability cueing in terms of learning behaviour or conscious awareness. If this removal has little or no effect and probability cueing can still be learnt, this may demonstrate the fluidness of this type of learning and offer insight into the mechanisms operating to aid probability cueing under different contexts. Understanding this could, in turn, indicate whether learning in this context is similar or dissimilar to visual search, adding to the debate of whether visual and foraging-type search processes use the same mechanisms. Broadly speaking, if learning does occur, this could also contribute to the argument that VEs are useful training tools for effective spatial learning, reflecting naturalistic search

behaviours, even if the environment is displayed on a desktop monitor. Thus, it is fundamental to understand how and why sensitivity to spatial cues differs (or is the same) across these environmental contexts.

In this Chapter, probability cueing under a virtual context will be examined. The aim of Experiment 1 (A and B) was to establish whether probability cueing could be observed in a VE and to examine learning over time. Experiment 2 expands on the VE task, by using a slightly more immersive large projection screen. Finally Experiment 3 steps away from a virtual context and instead aimed to replicate the probability cueing effects observed by Smith and colleagues (2010) by using a full-body search task. This experiment was conducted so that the transfer of probability cueing between virtual and laboratory space could later be examined.

3.2 Experiment 1A: Probability cueing in virtual space

This experiment investigated whether probability cueing could be learnt in a VE. This experiment forms the basis of further VE experiments in this Thesis. Participants were required to search the environment for a target that was hidden underneath one of 12 items spread throughout the VE. Unbeknownst to them, the target appeared more frequently on either the left or right side of space. This side was referred to as the cued side.

The environment was set-up similar to large-scale search tasks (e.g. Smith et al., 2010), insofar as items were presented on the floor for inspection and participants were required to navigate to find the target. Physical effort was, however, minimal

and physical movement was absent, as movement was controlled using the keys on a computer keyboard. The environment was simple to navigate with participants being able to view nearly all search items from their start position. Participants viewed the environment in an egocentric manner on each trial (i.e. from their viewpoint), and they consistently began their searches from the same position. This stabilised the egocentric coordinates. The presentation of search items and the cued side were held constant throughout the experiment, meaning the allocentric coordinates were also stabilised. These coordinates were fixed as previous full-body search tasks have suggested that reference frames need to be invariable for probability cueing to occur (see Experiment 2 in Smith et al., 2010). In VE research, it has also been demonstrated that the alignment of egocentric and allocentric factors facilitates spatial updating allowing subjects to memorise layouts of mazes and object locations (Burgess, 2006; Vidal, Amorim, & Berthoz, 2004). Thus, being consistent with both egocentric and allocentric factors may in turn encourage learning by enhancing the memory of cued targets within a virtual context.

It was predicted that, just as in visual search (e.g. Geng & Berhmann 2002) and large-scale search experiments (Smith et al., 2010), as the trials progressed, participants would learn the target likelihoods and bias their search towards the cued side of space. Four spatial learning measures were recorded to intricately examine probability cueing. It was predicted that search time on cued trials would be quicker than search time on uncued trials. It was hypothesised that more first visits would be directed towards locations on the cued side and that the overall visit rate (density)

would also be directed towards locations on the cued side. Finally, it was predicted that the mean number of visits would be greater on cued than uncued trials.

At the end of the experiment, participants were probed for their awareness of the probability cue. As well as learning the probability cue, it was predicted that this learning would be explicit in nature. This was because the task demands reflected in the VE were similar to the large-scale Smith et al. (2010) laboratory study. For example, effective navigational skill and active updating of spatial memory (e.g. tracking where targets were last found) are required to complete probability cueing within 3D VE and real space. This is unlike 2D visual search experiments that have demonstrated probability cueing to operate below conscious level (e.g. Geng & Berhmann, 2002). Task demands in this context are much less effortful, so for example, the egocentric viewpoint is static throughout the task as no navigation is required and instead a button press indicates target presence.

Alongside the probability cueing task, several other measures were recorded. These included: each participant's gender, their estimated mean number of hours they spent playing computerised games per week, the strength of their sense of direction (as measured by the Santa Barbara Sense of Direction Scale, SBSODS: Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002) and their laterality of handedness (as measured by the amended version (Schachter, 2000) of the Edinburgh Handedness Inventory, EHI: Oldfield, 1971). Relationships between these measurements and spatial learning were examined. They were chosen for several exploratory reasons. Firstly, it has been shown that males outperform females on spatial tasks (Coluccia & Louse, 2004; Voyer, Nolan, & Voyer, 2000; Voyer, Voyer, & Bryden, 1995).

Secondly, it has been shown that there is a complex relationship between handedness and spatial ability, although left handers tend to outperform right handers on some spatial tasks (Annett, 1992; Sanders, Wilson, & Vandenberg, 1982). Thirdly, self-reported sense of direction has been shown to relate to learning in VEs (Hegarty et al., 2002; Ventura, Shute, Wright, & Zhao, 2013). Finally, it has been found that increased video game experience relates to superior spatial ability and navigation in VEs (Richardson, Powers, & Bousquet, 2011; Ventura et al., 2013). To sum, it was predicted that relationships between spatial learning measures and hand lateralisation, sense of direction, gender and experience of virtual gaming, may occur.

3.2.1 Method

3.2.1.1 Participants

A total of 24 participants were recruited from the University of Nottingham, however four participants dropped out; one due to a technical problem with the task and three due to feelings of simulator sickness. This left a sample size of 20[1] (10 females). The age of the participants ranged from 19 to 35 years (M = 23.20; SD = 4.61). All participants had normal to corrected normal vision and, as recorded by the EHI, all were right handed (M = 77.50; SD = 17.95). Participants were offered £4 in exchange for their time.

[1] A priori power analysis revealed that a sample size of n = 20 was necessary to achieve a power of 96% to detect large effect sizes (d_z = 0.80, α = 0.05, df = 19) or 70% to detect a medium effect size (d_z = 0.50, α = 0.05, df = 19). This analysis was conducted on the most basic research design of a paired samples t-test with *trial type* as the factor, with two levels (cued and uncued). A sample size of n = 20 was therefore used in each of the experiments outlined in this chapter, as well as Experiment 4. Effect sizes were defined according to Cohen (1988, 1992).

3.2.1.2 Materials

The VE was created and displayed using MazeSuite computer software (Ayaz et al., 2008) and was run on a Stone desktop computer, running Microsoft Windows 7. The VE was displayed on a large Mitsubishi LDT422V LCD screen (42”). The details of the visual appearance of the environment and the array creations are in **Section 2.1.3**, but to recapitulate, the environment was viewed from a first-person perspective and consisted of a large square arena with a grass texture applied to the floor. The texture on two of the walls was divided so that it was half brick and half fence, although both joined together in the middle to create one solid wall. There was no ceiling to the arena, meaning that any space above the top of the walls appeared as a solid black colour. **Figure 3.1** demonstrates the appearance of the VE from a participant’s perspective.

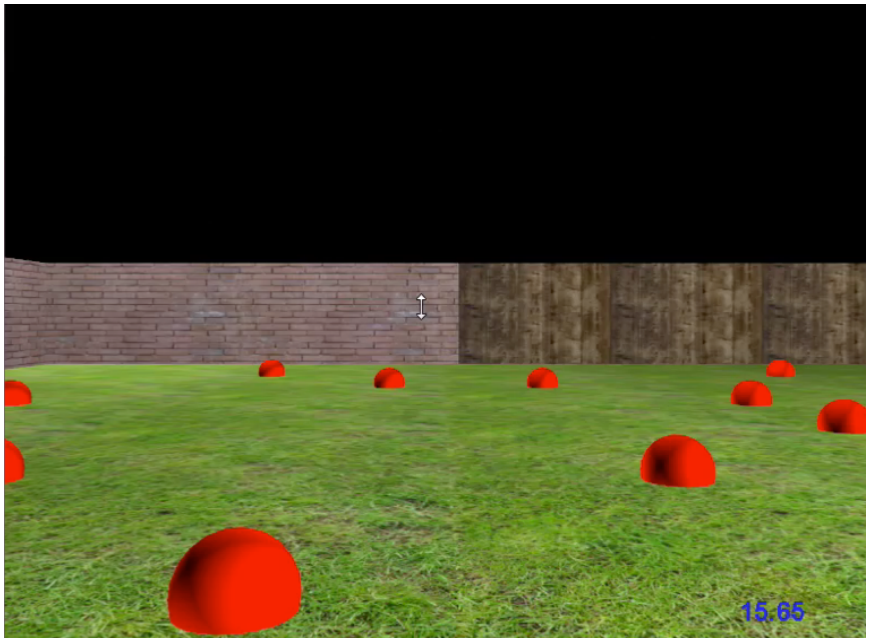


Figure 3.1 VE visual appearance for Experiments 1A and 1B.

On the floor of the environment there were 12 red hemispherical items representing the search locations. Each participant experienced a different search array (**Section 2.1.3** details how these arrays were made). The items were in a slightly smaller square arena of 4mx4m to allow the participant to view nearly all items from the start position.

A hidden, non-identifiable target was located under one of the 12 search items on each trial. The target was set to appear 80% of the time on one side of the VE (cued side) and 20% on the other (uncued side). Participants completed two blocks of 30 trials (60 in total). Participants were unaware of this manipulation and were instructed to find the target "as quickly as possible". Within each block, 24 trials contained a target on the cued side, and six trials contained a target on the uncued side. The target never repeated in the same location across successive trials to avoid repetition priming of the target's location (Walthew & Gilchrist, 2006; Maljkovic & Nakayama, 1996). Although the location of individual targets could not successively repeat, a series of trials in which the target appeared on the cued side, or uncued side, could repeat in a row. For example, the target could be at location 1, 5 then 4 – *all* locations on the cued side of space (whether that be left or right), but *not* the same location per se. Thus, the order of trials was pseudorandomised, with the only control being that the exact location of the target could not repeat on two consecutive trials.

The cued and uncued side of space was counterbalanced across participants, so that for 10 participants, the cued side was the left side, and vice versa for the other 10 participants. The sides were egocentrically defined, meaning the left and right were determined according to their viewing point. Assuming a plan view of the

environment, participants started from either the north or south side of the environment on the midline point. Start position was counterbalanced; 10 participants completed the task from the north and 10 participants completed the task from the south. The direction participants faced on each trial was always frontwards, with their 'back' towards the midline point where the two walls met and their 'front' facing outwards towards the search array.

3.2.1.3 Procedure

After signing a Consent Form, participants completed the EHI and the SBSODS. They were also asked to state, on average, how many hours per week they played computerised or virtual reality game(s). After this, participants were seated 1m away from the screen and were asked to complete two practice trials (one with the target located on the cued side of the array; one with the target located on the uncued side). Participants were required to explore the environment and navigate over each search location using the arrow keys on the computer keyboard, until they found the target. Presses on the 'up' and 'down' key permitted forwards and backwards movements whilst presses on the 'left' and 'right' key permitted rotational movements anti-clockwise and clockwise. When the target had been located (i.e. the participant had 'walked over' the target item), the trial ended and a success message appeared on screen ('Target found!') printed in MazeSuite default font and text size. A new trial was then initiated upon the participant pressing the 'Enter' key on the keyboard. After the practice trials, participants began the experiment, with a break after 30 trials.

After completing 60 trials, participants' awareness of target distribution was probed using the same method detailed by Smith et al. (2010). Participants were firstly asked whether they had used a strategy to search for the target, and if so, to detail this strategy. They were then asked if they had a 'sense' of where the target was most likely to be. Finally, participants were asked: "If I told you that the target was more likely to be on one side, would you be able to guess which one?". For this question participants had to make a forced-choice decision between "left" and "right". This questioning aimed to tap both explicit (Questions 1 and 2) and implicit (Question 3) awareness of the target location manipulation (Smith et al., 2010). The whole experiment lasted approximately 30 minutes.

3.2.2 Results

Each dependent variable was processed using a series of software stages including: MazeAnalyzer, LabVIEW and Microsoft Excel. The methods of how they were compiled are detailed in **Section 2.1.3.4**. These variables were then imported into SPSS software for further analyses. Each behavioural measure of spatial learning was analysed using either ANOVA's or *t*-test's[2], and they comprised: search time

[2] *Cohen's F* is used throughout this Thesis as a measurement of effect size for ANOVA analysis. Partial eta square (ηp^2) for each factor was firstly calculated in SPSS software and this value was then input into G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007) to produce effect sizes.
Cohen's f is interpreted using the following cut-offs: **small** = 0.10; **medium** = 0.25; **large** = 0.40.
Cohen's f allows for easier interpretation and comparison across all variants of design, in comparison to ηp^2, especially when repeated measures factors are introduced (see Bakeman (2005), p.380 for a useful example of inflated ηp^2 across study designs). It is specifically appropriate for ANOVA designs, rather than *t*-test's, that use *Cohen's d or Cohen's* d_z.
When *t*-tests were used, *Cohen's d* was instead calculated using the software G*Power 3.1 (Faul et al., 2007). *Cohen's* d_z is reported for paired sample's *t*-test's (as described by Lakens (2013), p.4: "Z alludes to the fact that the unit of analysis is no longer X or Y, but their difference").

(median per trial type, seconds), first visits (percentage to the cued side), density (percentage to the cued side), and number of visits (mean total per trial type). Analyses were also conducted, using similar statistical tests, to examine whether the laterality of the cue (left or right side of the array) influenced search performance. This was then followed by an examination of the Post-Experiment Questions using binomial tests, as well as correlational analyses to examine the relationships between probability cueing and the questionnaire data.

Pre-analysis

Upon reviewing participant data, it was found that some participants were erroneously revisiting some target locations. On these occasions, it 'looked like' the location had been visited, but the active region that the target encompassed was in fact missed and the trial was not ended. The participant therefore carried on searching. This occurred in 1.5% of trials (18 out of 1200 trials). This was corrected for by manually examining each trial, per participant. Firstly, the image of the travelled path recorded during the trial was inspected (see **Figure 2.3** for an example of this). If it was suspected that a trial was erroneous, a video recording of it, taken from the participant's perspective and mapping the exact path travelled, was watched to validate this. If an erroneous revisit was confirmed, the region of interest size was increased slightly in MazeAnalyzer, so that measures were taken within this slightly enlarged area.

Cohen's d/d_z was interpreted using the following cut-offs: **small** $d = 0.20$; **medium** $d = 0.50$; **large** $d = 0.80$.

3.2.2.1 Behavioural results

Search time

Median search time on cued and uncued trials was calculated for this dependent variable (see **Section 2.3** for an explanation as to why the median was used). A repeated measures ANOVA with the factors *trial type* (two levels: cued trials; uncued trials), and *block* (two levels: Block 1 [first 30 trials]; Block 2 [second 30 trials]) was firstly conducted. Participants were significantly quicker to find the target when it was located on the cued side of space (M = 13.43s, SD = 6.99) as opposed to the uncued side of space (M = 19.99s, SD = 8.51) ($F(1,19) = 7.15$, $p = 0.015$, $f = 0.61$). Search time was also significantly slower for Block 1 trials (M = 17.37s, SD = 5.26) than in Block 2 trials (M = 16.04s, SD = 5.30), alluding to a learning effect across blocks ($F(1, 19) = 4.69$, $p = 0.043$, $f = 0.50$). These main effects are illustrated in **Figure 3.2**. There was no interaction between the two factors ($F < 1$, $f = 0.07$).

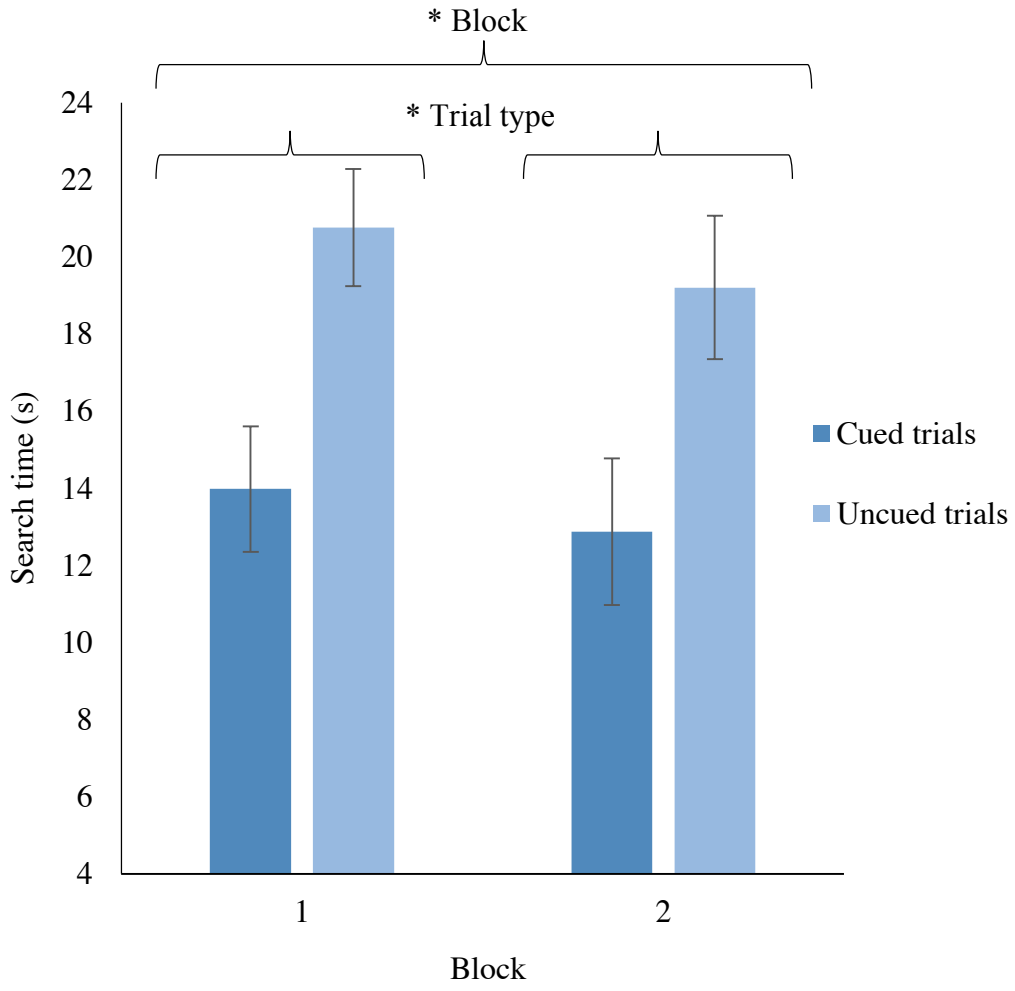


Figure 3.2 Reduction in median search time on cued trials compared to uncued trials (main effect of trial type) and a reduction in overall search time across the two blocks (main effect of block). Error bars represent +/-1 standard error of the mean, *$p < 0.05$.

Search time and the cued side

Although the cued (and uncued) side was counterbalanced across the left and the right side of the VE, there is a possibility that the laterality of the cue influenced search performance. A mixed ANOVA was conducted with the previous factors *block* and *trial type*, plus *cued side* (two levels: left, right) as an additional between-subjects factor on median search time. As with the previous results, this mixed ANOVA

indicated a main effect of trial type ($F(1, 18) = 7.42$, $p = 0.014$, $f = 0.64$), and a main effect of block ($F(1, 18) = 5.08$, $p = 0.037$, $f = 0.53$), as well as a no significant interaction between these two factors ($F < 1$, $f = 0.006$). There was no main effect of cued side ($F < 1$, $f = 0.063$), suggesting that probability cueing still occurred irrespective of whether the left ($M = 16.38$s, $SD = 7.39$) or right side ($M = 17.03$s, $SD = 7.39$) of egocentric space was cued. Cued side also did not interact with probability ($F(1, 18) = 1.72$, $p = 0.206$, $f = 0.31$) or block ($F(1, 18) = 2.59$, $p = 0.125$, $f = 0.38$). There was also a non-significant three-way interaction between the factors ($F(1, 18) = 1.23$, $p = 0.282$, $f = 0.26$).

First visits

First visits were coded as the percentage of trials in which the first inspection was directed to the cued side of space. To ascertain whether this was significantly greater than chance, one-sample *t*-tests were conducted against a test statistic of 50%. For Block 1, this yielded a significant result ($t(19) = 2.30$, $p = 0.033$, $d = 0.51$; $M = 68.33\%$, $SD = 35.60$). First visits were also directed significantly more to the cued side in Block 2 ($t(19) = 2.22$, $p = 0.039$, $d = 0.50$; $M = 69.00\%$, $SD = 38.30$). A paired samples *t*-test was conducted to ascertain whether the preference for the cued side changed across the two blocks of the experiment, but no significant difference was observed ($t(19) = -0.24$, $p = 0.814$, $d_z = 0.05$). Collectively these results suggest that participants biased their search towards the cued side of space relatively early in the task, and that this was not reliably modified over the course of the experiment. This result is illustrated in **Figure 3.3**.

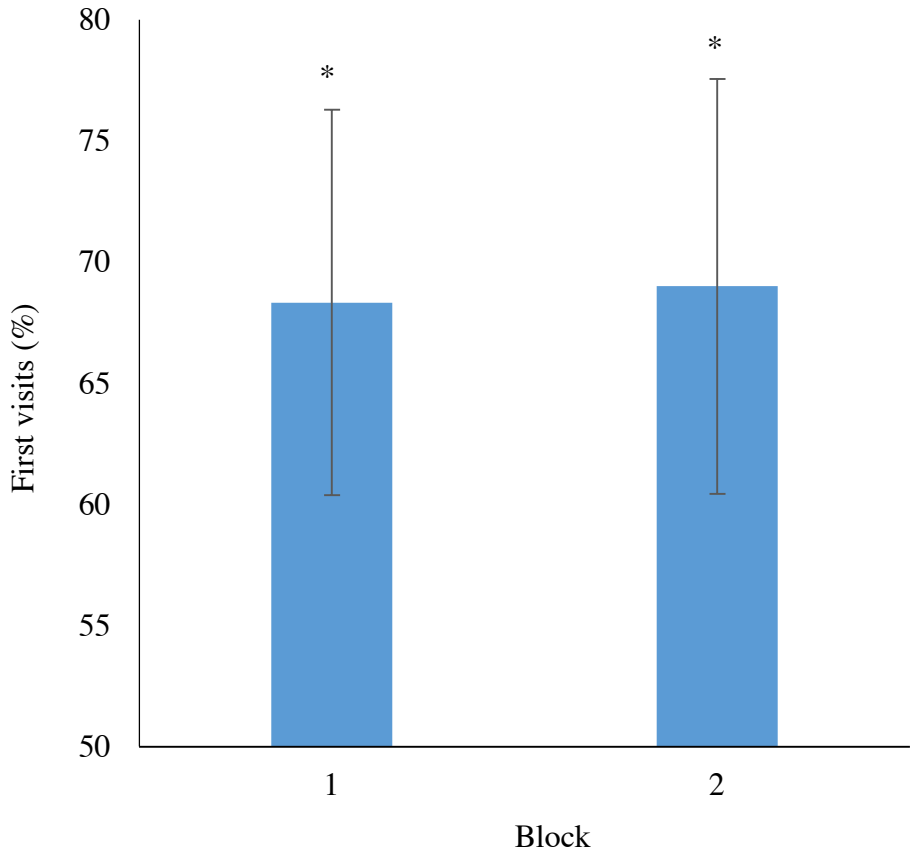


Figure 3.3 Percentage of first visits were significantly above 50% chance in Block 1 and 2. Error bars represent +/-1 standard error of the mean, *$p < 0.05$.

First visits and the cued side

A mixed ANOVA with *cued side* and *block* was conducted to examine whether cue laterality influenced first visits. There was no significant main effect of block ($F(1, 18) = 1.91, p = 0.183, f = 0.05$). There was also no significant main effect of cued side ($F < 1, f = 0.06$) and no interaction between these two factors ($F < 1, f = 0.17$). Thus, although first visits were biased to the cued side, it did not make a difference whether the cued side was on the left ($M = 71.00\%$, $SD = 40.03$) or the right ($M = 66.33\%, SD = 33.47$).

Density

The density measure reflected the percentage of overall visits that were directed to locations in the cued side of space, thus probability cueing would be reflected in a higher density of inspections in this region. To test whether this was significantly different to chance, one-sample *t*-tests were conducted against a test statistic of 50%. These *t*-tests revealed that for Block 1 ($t(19) = 4.11$, $p = 0.001$, $d = 0.92$; $M = 68.96\%$, $SD = 20.62$) and Block 2 ($t(19) = 4.34$, $p < 0.001$, $d = 0.97$; $M = 71.52\%$, $SD = 22.19$) significantly more visits were directed at the cued side than chance level. This is illustrated in **Figure 3.4**. Similarly to first visits, a paired samples *t*-test demonstrated no significant effects across the two blocks of trials ($t(19) = -1.40$, $p = 0.177$, $d_z = 0.31$).

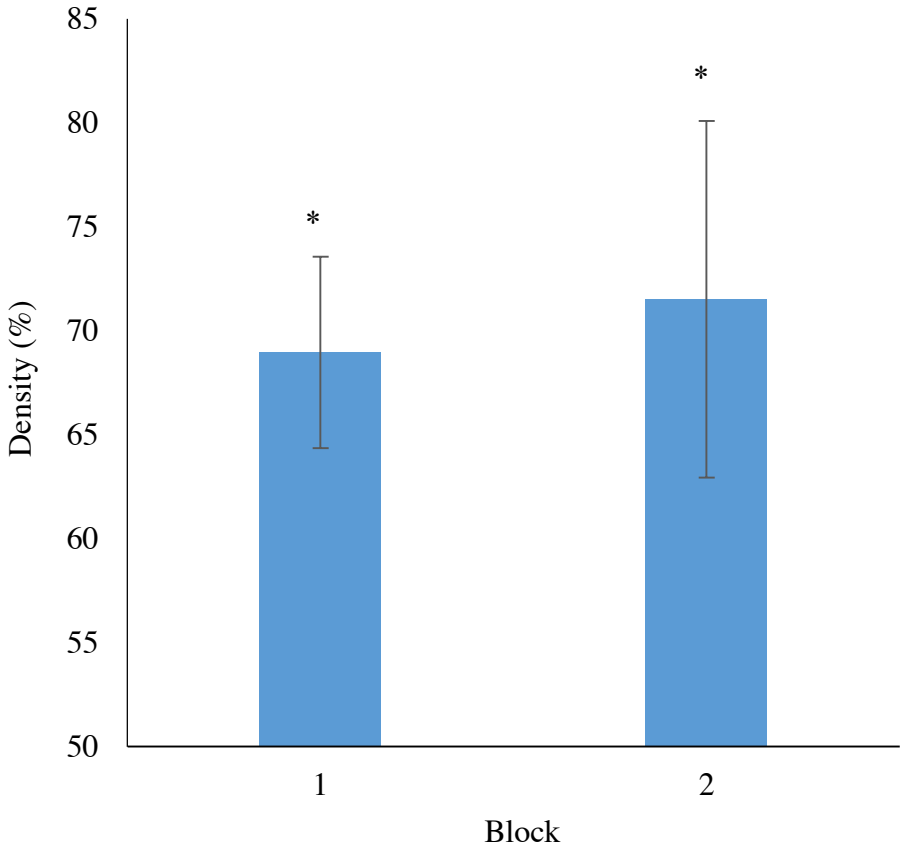


Figure 3.4 Density was significantly above 50% chance for Block 1 and Block 2. Error bars represent +/-1 standard error of the mean, *$p < 0.05$.

Density and the cued side

A mixed ANOVA with *cued side* and *block* was conducted on density to examine whether the cued side influenced search performance. This ANOVA showed no significant main effect of block ($F(1, 18) = 1.91, p = 0.183, f = 0.33$) and cued side ($F < 1, f = 0.10$). There was also no interaction between these two factors ($F < 1, f = 0.16$). In line with search time and first visits, the cue had no effect on density whether it was on the left ($M = 72.20\%$, $SD = 22.91$) or right side of space ($M = 68.27\%, SD = 19.70$).

Number of visits

For this measure, the mean of the total of the number of visits for cued and uncued trials was calculated. Probability cueing was reflected in a lower overall number of visits on cued trials, since inspections would be biased towards the likely target location, in comparison to uncued trials, which would engender more inspections and searching. A repeated measures ANOVA was conducted to examine whether there was a difference between the mean number of visits on these two trial types. Overall, there were significantly more visits on uncued trials (M = 8.76, SD = 2.65) than cued trials (M = 6.08, SD = 2.02), suggesting a more effortful search when the target appeared on the uncued side of space ($F(1, 18) = 7.90$, $p = 0.011$, $f = 0.65$). **Figure 3.5** demonstrates this effect. The number of visits did not change between Block 1 (M = 7.72, SD = 1.83) and Block 2 (M = 7.12, SD = 0.99) ($F(1, 18) = 1.62$, $p = 0.218$, $f = 0.29$), and there was no interaction between factors ($F < 1$, $f = 0.15$).

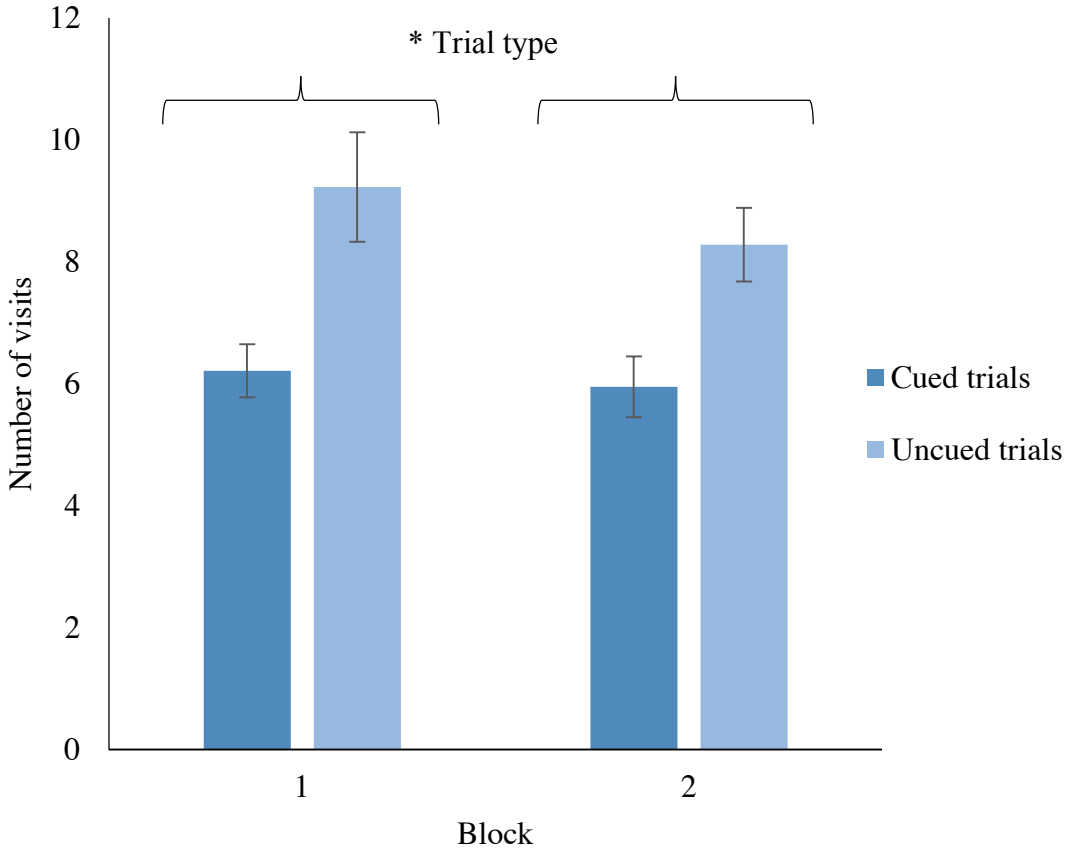


Figure 3.5 A significant reduction in the number of visits to items on cued trials compared to uncued trials. Error bars represent +/-1 standard error of the mean, *$p < 0.05$.

Number of visits and the cued side

Trial type, *block* and *cued side* were subjected to a mixed ANOVA. Replicating the results from the previous ANOVA, a main effect of trial type ($F(1, 18) = 8.00$, $p = 0.011$ $f = 0.67$) was observed, whilst a no significant main effect of block ($F(1, 18) = 1.55$, $p = 0.228$, $f = 0.29$) was found. There was no significant interaction between trial type and block ($F < 1$, $f = 0.15$). There was also no significant main effect of cued side ($F < 1, f = 0.04$), and neither did cued side interact

with block ($F < 1$, f = 0.11) nor trial type ($F(1, 18) = 1.25$, $p = 0.279$, $f = 0.23$). Finally, the three-way interaction between trial type, block and cued side did not reach significance ($F < 1$, $f = 0.04$). Overall, whether the left side ($M = 7.37$, $SD = 3.46$) or right side ($M = 7.46$, $SD = 2.76$) was cued, had no effect on the mean number of visits.

3.2.2.2 Individual differences

Scoring the Post-Experiment Questions

For Question 1 participants were asked whether they had used a strategy to find the target. If they said "Yes", they were asked to explain this. For the second question, participants were asked if they had a sense of where the target was most likely to be. For the final question, participants were told that the target was more likely to be appear within one side of space, and were asked to guess whether this was the left or right. A correct judgement for this question did not indicate conscious awareness as it required a forced-choice prompt. **Table 3.1** outlines some examples of phrases and key words that were coded as implicit or explicit knowledge of the target's location.

Table 3.1 Examples of phrases and key words coded as implicit or explicit knowledge of the target's location.

Below conscious level	Above conscious level
Travel: "around in circles"	**Travel:** left, right, brick fence, east, west, anticlockwise, clockwise
Route: "followed the pattern of the search items", "I went somewhere different on each trial",	**Direct reference:** "I felt like the target...", "The target seemed to/often appeared...", "I had a feeling that the target was...", "The target was usually...", "The target was likely to be..."
Distance: "tried to cover as many locations as possible in the shortest distance", "started with search locations closest to me and worked my way to the furthest away"	**Initial search:** "Always started search to the left/right"

Post-Experiment Questions

Out of 20 participants, 75% reported using a strategy to find the hidden target. A binomial test indicated this to be significantly greater than 50% chance level (p = 0.041). However, when participants were probed further about their strategies, only 20% of participants reported an awareness of the target's location or using the separate sides of the virtual space to guide their search (*binomial*, p = 0.012). This suggests that although strategies were common, a very minimal number of participants reported an awareness of the probability cue.

For the second question, participants were asked if they had a sense of where the target was most likely to be. 70% of participants answered 'no' to this question indicating that most participants were unable to sense the target's probable location (*binomial*, p = 0.115). Finally, 95% of participants correctly guessed the cued side

(*binomial*, $p < 0.001$), when presented with a forced-choice probe. Results for each individual question are summarised in **Table 3.2**.

Table 3.2 Experiment 1A - Post-Experiment Questions. Participants identified the target's location when given a force-choice probe. *$p < 0.05$, **$p \leq 0.001$.

Question	Answer	Binomial result
1A - Strategy *"Did you use a strategy to search for the target in the environment"*	Yes: 75% ($n = 15$) No: 25% ($n = 5$)	***p* = 0.041***, in the direction of more participants reporting a strategy.
1B - Strategy *"If YES please explain your strategy"*	Awareness: 20% ($n = 4$) No awareness: 80% (n =16)	***p* = 0.012***, in the direction of no awareness of the probability cue.
2 - Sense *"Did you have a sense of where the target was most likely to be in the environment?"*	Yes: 30% ($n = 6$) No: 70% ($n = 14$)	$p = 0.115$, less than 50% chance level.
3 - Final probe *"If I told you that the target was more likely to appear on one side, would you be able to guess which one?"*	Correct judgement: 95% ($n = 19$) Incorrect judgement: 5% ($n = 1$)	***p* < 0.001****, more participants correctly identified the cued side.

Scoring other questionnaires

At the beginning of the experiment, participants were required to complete a series of questionnaires: the EHI, the SBSODS and to report, on average, how many hours per week they spent playing computerised games. The EHI scores were calculated using an amended scoring system (Schachter, 2000). Details of this scoring method are in **Appendix 3,** along with the amended EHI itself. Scores around 100 represented strong right lateralisation, -100 represented strong left lateralisation, and 0

represented no strong preference. For the SBSODS, a percentage score was calculated, with higher values representing a greater perceived sense of direction.

Questionnaire Data

Cueing effect measures were calculated for each of the dependent variables which indicated the strength of learning. The more positive the individual value, the stronger the sensitivity to probability cueing. For search time and number of visits, the cueing effect was derived by calculating the difference between uncued and cued trials for each respective measure; this was calculated separately for each block and then a mean value between these two blocks was produced per participant. Cueing scores for first visits and density were derived by taking the combined mean for Block 1 and Block 2. These cueing scores were then entered in two-tailed Pearson's Product-Moment Correlations, along with the questionnaire data: EHI score, SBSODS score and number of gaming hours. A Point-Biserial Correlation[3] was conducted to examine whether gender was related to any of the spatial learning measures and the other questionnaire data.

The results from the correlations, including alpha and *r*-values, can be found in **Table 3.3**. There were significant relationships between all the cueing effect measures ($p < 0.001$). These correlations were positive, suggesting that high sensitivity to probability cueing on one dependent variables was related to high sensitivity to another. There were no significant relationships between any of the

[3] A Point-Biserial Correlation is similar to a Pearson's correlation (and is also conducted using the same method in SPSS), but is used when one variable is defined as discretely dichotomous (Field, 2013). For example, there is no underlying continuum between the two categories of sex.

individual differences measures (gender, EHI, SBSODS, or gaming hours) and the cueing effects ($p > 0.05$). None of the individual differences measures were related, apart from a significant relationship between gender and EHI (r_{pb}= -.54, p = 0.013). This relationship was negative[4], suggesting that females reported a stronger right hand lateralisation than males.

[4] The significant correlation between gender and EHI is interpreted as negative as males were coded as '0' and females as '1'. Thus, if this variable was recoded the other way around (e.g. *males = 1*, *females = 0*), a positive relationship would incur. The sign of the coefficient is dependent upon the category coding, yet interpretation incurs the same meaning (Field, 2013).

Table 3.3 Experiment 1A – Pearson's Product-Moment Correlations (r and α) and a Point-Biserial Correlation (r_{pb} and α) for the cueing effect and questionnaire measures, $^{*}p < 0.05$, $^{**}p \leq 0.001$.

		1.	2.	3.	4.	5.	6.	7.	8.
1. Search cueing effect		-							
2. First visits cueing effect	*r*	**.75****	-						
	α	**< 0.001**							
3. Density cueing effect	*r*	**.86****	**.97****	-					
	α	**< 0.001**	**< 0.001**						
4. Number of visits cueing effect	*r*	**.88****	**.79****	**.89****	-				
	α	**< 0.001**	**< 0.001**	**< 0.001**					
5. EHI	*r*	.39	.18	.29	.34	-			
	α	0.093	0.438	0.219	0.137				
6. SBSODS	*r*	.30	.18	.19	.11	.27	-		
	α	0.198	0.437	0.434	0.640	0.242			
7. Gaming hours	*r*	-.32	-.01	-.14	-.34	-.27	-.22	-	
	α	0.166	0.965	0.561	0.142	0.245	0.361		
8. Gender	r_{pb}	-.16	.04	-.39	-.26	**-.54***	.08	.29	-
	α	0.511	0.860	0.871	0.267	**0.013**	0.740	0.221	

3.2.3 Discussion

Experiment 1A investigated whether probability cueing could be observed in a VE, using a general paradigm akin to that of the full-body search paradigm described by Smith et al. (2010). This was achieved by designing a 3D, VE task that defined a cued and uncued side of space by manipulating the underlying statistical properties of a target's location, but with task demands restricting physical movement. Probability cueing was established, as demonstrated by all measures of spatial learning. Participants spent less time searching when the target was located on the cued side of space. First visits were more likely to be directed towards the cued side of space. Furthermore, search items within the cued side were visited more frequently than chance, as evidenced by the density measure. The number of visits on uncued trials were also higher than cued trials, suggesting that more locations were inspected when targets were located within this side. Furthermore, the side that was cued (left or right) had no effect on any of the dependent variables, suggesting that laterality of the cue was unimportant to learning. Overall, these results indicate that probability cueing is possible in a VE and that participants can exploit the underlying statistical properties of a search array.

The Post-Experiment Questions suggested that learning the target's probable location was below conscious level – participants acknowledged the probability cue when forced to guess the cued side in the final question. This search strategy is in line with results from visual search literature, such as Geng and Behrmann (2002). Geng and Behrmann (2002) asked participants one question at the end of their experiment:

"Did you feel that the target was more likely to appear in one location or region, or did you feel that targets were well distributed?" (p.521). They reported that 75% of younger adults expressed no awareness of the targets location. Similarly, 80% of the participants in this current study were unable to provide a strategy that demonstrated awareness of the cued side, and 70% of participants did not have a 'sense' of the targets likely location. 95% could guess the cued side, although this does not suggest conscious awareness as participants were informed that one side was cued and were required to make a forced-choice judgement.

The results from the Post-Experiment Questions in this experiment contrast with those from real-world probability cueing studies. In Experiment 2, Smith et al. (2010) report that efficient search relied on explicit knowledge of the probability cue. In the present experiment, it was predicted that probability cueing would reach conscious awareness in a VE as the search space is more like these tasks than visual search. On the other hand, the task demands of the VE did not require any reliance on physical movement, vestibular and multisensory information; similar to visual search tasks that involve none of this information. This may be why Post-Experiment Question results are parallel to visual search studies rather than real-world search tasks.

Although results from Experiment 1A seem to suggest that visual and virtual probability cueing comprise of a shared search mechanism that operates below a conscious level, it is important to highlight that saccadic preference for a specific region (or side) of space (Jiang et al., 2014) is arguably not the same as a representational preference in a virtual 3D environment. Furthermore, it is also

important to highlight that preferences demonstrated in visual and virtual search may also be different to preferences created in real space. In a VE, objects are presented in 'representational space' (Mcpherson & Nunes, 2004). This means that the space that search items occupy is not real and the user can only interact with the environment and the objects within the realms of the virtual area. Mental representations of the spatial properties and relationships between objects and landmarks, need to develop quickly and accurately for effective navigation, as the world is a *representation* (Vinson, 1999). This can sometimes be difficult to achieve as, in general, VEs have great computational demands but with minimal support, for example, some environments may have a lack of landmarks. This can cause discrepancies between the user input or skills and the outcome, for example, a higher rate of navigational error leading to disorientation and lack of accurate memory during object recall (Kirschen et al., 2000). In contrast, during 2D visual search tasks and real-world search, spatial properties and relationships between objects are not a representation; they instead occupy physically stable locations.

To evidence this, some studies have examined how individuals develop mental representations of space and how these representations differ or are similar across contexts (e.g. Péruch, Belingard, & Thinus-Blanc, 2000; Vinson, 1999). As one move's through space, spatial knowledge about the environment is acquired in the form of a mental map (Péruch et al., 2000). These mental maps or representations have been studied extensively under real-world (e.g. Rose et al., 2000), virtual (e.g. Belingard & Peruch, 2000) and 2D visual restraints (e.g. Mcnamara, Rateliff, & Mckoon, 1984). One of the first studies to examine these differences was by Arthur,

Hancock and Chrysler (1997). They found that a static, single viewpoint condition (akin to visual, 2D environments) incurred greater object location map drawing accuracy than during VE and real-world conditions. This suggests that the mental representations created in the virtual and real-world set-ups were very similar in nature, unlike those created from a static view-point.

The study by Arthur et al. (1997) emphasises that whilst on the surface, acquired spatial knowledge under one context may appear to 'act' like another, the underlying accuracy of a mental representation may differ. Task demands may also be similar, but mental representations of space may still differ from each other; this point is examined later in this Thesis by the transfer of probability cueing. In the present experiment, although the learning process may be below conscious expression, it may also have a different mental representation and behaviourally the preference to the cued side may also differ because of the representational space it is built within.

Although the results from Experiment 1A indicate probability cueing, the design of the experiment meant that learning over smaller epochs of time could not be inspected. This is because trials were fully randomised within each block, meaning that the statistical information unfolded differently for each participant. The behavioural results demonstrated that density, number of visits, and first visits, reflected a preference for the cued side of space within Block 1, and that this was not reliably modified in Block 2, with no differences found in performance between the two blocks. In comparison, there was a difference between the two blocks of trials for search time. This may be because this variable is dependent on speed, in comparison to the other spatial learning measures that are instead independent of speed.

Potentially, factors such as experiencing simulator sickness or poor handling of the controls, could contribute towards the speed at which a participant travels. In turn, factors such as these that cannot be avoided or controlled for, but could be the reason why there were differences between the two blocks for search time only.

A finer measurement may be required to gain a clearer picture of when learning emerges. This has been attempted in a small number of published probability cueing studies (Jiang & Swallow, 2013; Kabata & Matsumoto, 2012). For example, in a visual search paradigm, Kabata and Matsumoto (2012) divided 400 trials so that 20 trials were in each block for analysis. They found that probability cueing seemed to occur from trial 80, suggesting that learning occurs relatively early in the trial sequence. This may be the case in a VE context too, as in Experiment 1A probability cueing for some of the measures was not modulated across the two blocks. Thus, learning may reach an optimum very quickly, and further biases in search performance may be difficult to build upon over the course of trials once it has done so.

Therefore, a trial structure was designed so that it could be fractionated into smaller epochs than in Experiment 1A. Previous studies (e.g. Jiang & Swallow, 2013; Kabata & Matsumoto, 2012) have failed to fully discuss how exactly this was achieved in their respective paradigms. Simply analysing the data in smaller epochs with differing amounts of cued and uncued trials across each epoch may not provide a valid approach with the effect of block enhanced or skewed. For example, if the blocks are divided up into 20 trials per block, participant X may experience Block 1 consisting of all cued trials, whereas participant Y may experience two cued trials in

the same block. It is debateable whether dividing the blocks and comparing in this way is accurate, as each participant may experience different amounts of cued/uncued trials, which may influence the way the probability cue is learnt. Learning over time was therefore examined in closer detail in Experiment 1B.

3.3 Experiment 1B: Examining probability cueing over time

This experiment investigated probability cueing over time in a VE, by dividing the trial order into smaller epochs. The experiment was identical to Experiment 1A in every detail except for trial order: the two blocks of 30 trials were divided into epochs to enable learning over time to be closely tracked. It was hypothesised that learning would occur early, with the epochs within Block 1 showing greater differences in the dependent variables for cued and uncued trial types than epochs later in Block 2. This is because in Experiment 1A, density, first visits and number of visits showed no difference between Block 1 and Block 2, suggesting that learning had already peaked. In comparison, and again equal to Experiment 1A, search time may develop more slowly over time, with epochs later in the trial sequence shower greater differences. It was also predicted that this learning would operate below conscious level, with participants reporting little knowledge of the targets' location.

3.3.1 Method

3.3.1.1 Participants

20 participants were recruited from the University of Nottingham (13 females); originally 22 participants were recruited but two dropped out due to feelings of sickness. The age of the participants ranged from 18 to 28 years (M = 20.50; SD = 3.10). All participants had normal to corrected normal vision and, as recorded by the EHI, all but one participant was right handed (left handed participant score: -45; right handed participants: M = 77.12; SD = 22.26). Individuals were not allowed to participate if they had participated in Experiment 1A, or any other related studies conducted by the Experimenter or the research group. Participants were given course credits in exchange for their time.

3.3.1.2 Materials

The VE and set-up outlined in Experiment 1A (**Section 3.2.1.2**) was also used in this experiment. The only difference between Experiment 1A and 1B was the trial order. There were two blocks of 30 trials (60 in total), and within each block the trials were divided up into three smaller epochs of 10 trials, containing two uncued trials and eight cued trials (six epochs in total). The target appeared 80% of the time on the cued side and 20% of the time on the uncued side. As with Experiment 1A, the target's location was pseudorandomised so that the target could not repeat in is location across successive trials.

3.3.1.3 Procedure

This experiment followed the same procedure as Experiment 1A (**Section 3.2.1.3**). In brief, participants were asked to complete two practice trials and 60 trials defined by cued and uncued target location probabilities, with a break between trial 30 and trial 31. Participants were unaware of the target's spatial likelihoods. After completing the 60 trials, awareness of probability cueing was probed using the same Post-Experiment Questions as in Experiment 1A, although if participants reported a 'sense' of the targets location for Question 2, they were asked to define this. This extra question was added so that the participant could clarify where they sensed the target was most likely to be. The whole experiment lasted approximately 30 minutes.

3.3.2 Results

2.42% of data was pre-processed for erroneous revisits. Statistical tests were conducted to examine learning across the trial sequence to a finer grain of measurement[5]. In this Epoch analysis, six epochs of 10 trials were analysed, with each epoch including data from two uncued trials and eight cued trials.

3.3.2.1 Behavioural results

Search time

[5] Analysis was conducted in Experiment 1A to explore the effect of the egocentrically cued side; this consistently had no effect on performance. In Experiments 1B, 2, 3 and 4, the cued side also had no effect on any spatial learning measures ($p > 0.05$), but is not reported in text.

Median search time was calculated for each epoch. A repeated measures ANOVA with *epoch* (six levels: Epoch 1, Epoch 2, Epoch 3, Epoch 4, Epoch 5, Epoch 6) and *trial type* (two levels: cued, uncued) was conducted. Mauchley's test indicated that the assumption of sphericity had been violated for epoch ($\chi^2(14) = 31.95$, $p = 0.004$) and the interaction effect between epoch and trial type ($\chi^2(14) = 35.07$, $p = 0.002$), therefore degrees of freedom were corrected to Greenhouse-Geisser estimates of sphericity (epoch: $\varepsilon = 0.66$; epoch x trial type: $\varepsilon = 0.70$). The ANOVA revealed no significant main effect of epoch ($F(3.30, 62.70) = 2.40$, $p = 0.071$, $f = 0.36$). There was also no significant main effect of trial type ($F(1, 19) = 3.61$, $p = 0.073$, $f = 0.44$). There was no interaction effect between the two factors ($F < 1$, $f = 0.16$). **Table 3.4** outlines the means and standard deviations for each of the epochs.

Table 3.4 Means and standard deviations for search time (s) overall and for each trial type, for all epochs.

	Epoch 1	**Epoch 2**	**Epoch 3**	**Epoch 4**	**Epoch 5**	**Epoch 6**
Cued trials	*M* = 16.32 *SD* = 7.37	*M* = 13.05 *SD* = 6.96	*M* = 12.37 *SD* = 5.97	*M* = 13.67 *SD* = 6.31	*M* = 12.62 *SD* = 5.35	*M* = 13.23 *SD* = 7.38
Uncued trials	*M* = 20.97 *SD* = 14.37	*M* = 16.81 *SD* = 9.91	*M* = 16.37 *SD* = 10.47	*M* = 18.76 *SD* = 10.83	*M* = 17.55 *SD* = 14.13	*M* = 21.69 *SD* = 15.52
Overall	*M* = 18.65 *SD* = 11.52	*M* = 14.93 *SD* = 8.66	*M* = 14.37 *SD* = 8.65	*M* = 16.23 *SD* = 9.12	*M* = 15.08 *SD* = 10.84	*M* = 17.46 *SD* = 12.74

First visits

First visits to the cued side from Epoch 1 ($M = 57.00\%$, $SD = 33.10$) to Epoch 2 ($M = 57.00\%$, $SD = 37.99$) did not change. Neither of these epochs were significant above 50% chance level when exposed to two one-sample *t*-test's (Epoch 1: $t(19) =$

0.95, $p = 0.356$, $d = 0.21$; Epoch 2: $t(19) = 8.24$, $p = 0.410$, $d = 0.18$). Epoch 3 (M = 60.00%, SD = 36.99) had a slight numerical increase in first visits, whilst Epoch 4 (M = 56.50%, SD = 40.04) decreased. First visits for these two epochs also did not reach significance above 50% chance level (Epoch 3: $t(19) = 1.21$, $p = 0.242$, $d = 0.27$; Epoch 4: $t(19) = 0.73$, $p = 0.477$, $d = 0.16$). Epoch 5 (M = 57.50%, SD = 42.78) and Epoch 6 (M = 59.00%, SD = 42.42) had a marginal increase in first visits, but again, these were not significantly above chance level (Epoch 5: $t(19) = 0.78$, $p = 0.443$, d = 0.18; Epoch 6: $t(19) = 0.95$, $p = 0.355$, $d = 0.21$).

Mauchley's test showed that the assumption of sphericity for *epoch* was violated in a one-way repeated measures ANOVA ($\chi^2(14) = 67.99$, $p < 0.001$), with first visits as the dependent variable. Greenhouse-Geisser was used to adjust the degrees of freedom ($\varepsilon = 0.40$). First visits did not significantly change across the epochs of trials ($F < 1, f = 0.08$).

Density

Six one-sample *t*-tests were used to examine density as the experiment progressed. Each epoch consisted of the overall density to cued trials, per 10 trials. For Epoch 1 ($t(19) = 3.49$, $p = 0.002$, $d = 0.78$; M = 64.38%, SD = 18.45), Epoch 2 ($t(19) = 3.22$, $p = 0.004$, $d = 0.72$; M = 65.86%, SD = 22.02) and Epoch 3 ($t(19)$ = 2.38, $p = 0.028$, $d = 0.53$; M = 62.78%, SD = 23.99) the percentage of visits was more likely to be towards the cued side of space, than chance level. These significant results, in the same direction, were also reflective in Epoch 4 (M = 62.55%, SD = 23.56; $t(19) = 2.38$, $p = 0.028$, $d = 0.53$), Epoch 5 ($t(19) = 2.21$, $p = 0.039$, $d = 0.49$;

M = 62.85%, SD = 25.96) and Epoch 6 ($t(19)$ = 2.70, p = 0.014, d = 0.60; M = 64.90%, SD = 24.71). These results are plotted in **Figure 3.6**.

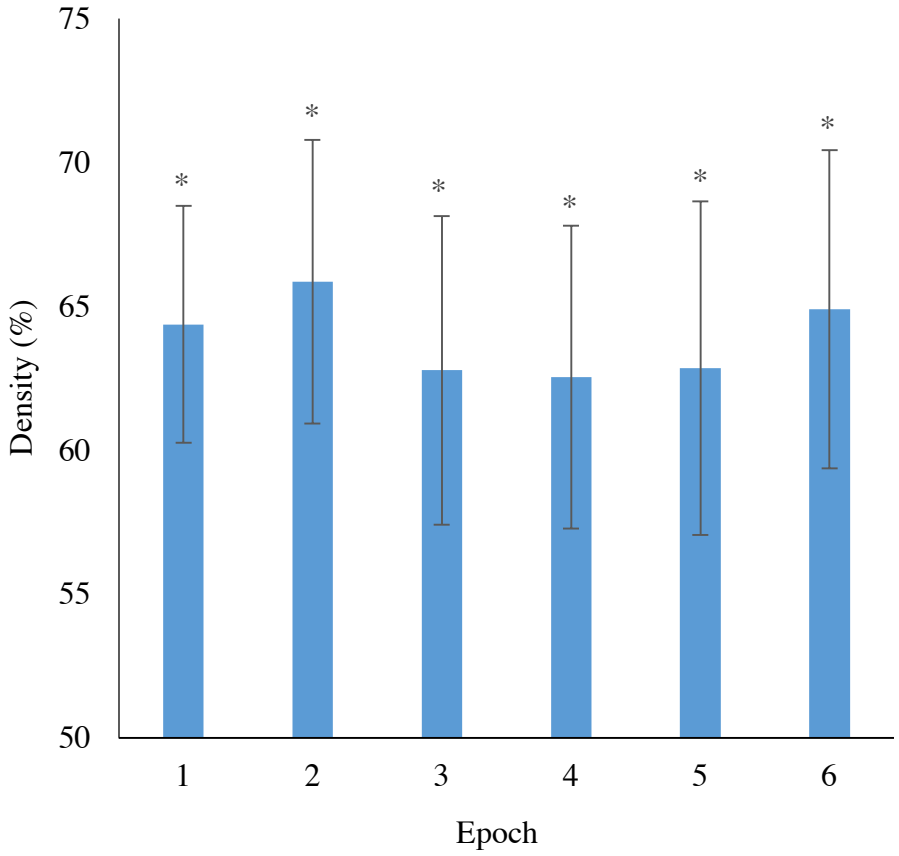


Figure 3.6 Density was significant above 50% chance across all epochs. Error bars represent +/-1 standard error of the mean, *$p < 0.05$.

A one-way ANOVA with *epoch* as the factor investigated whether density changed across the trial sequence. Mauchley's test of sphericity was not met ($\chi^2(14)$ = 42.86, $p < 0.001$) so Greenhouse-Geisser values were examined ($\varepsilon = 0.48$). Epoch was not significant ($F < 1, f = 0.12$) suggesting that the percentage of visits to the cued side stayed the same throughout the trial sequence.

Number of visits

A repeated measures ANOVA was used to examine the differences between *epochs* and *trial type* on the number of visits. Mauchley's test was violated for epoch ($\chi^2(14) = 36.83, p = 0.001$) and the epoch by trial type interaction ($\chi^2(14) = 34.99, p = 0.002$) so Greenhouse-Geisser values were used for this analysis (epoch: $\varepsilon = 0.59$, epoch x trial type: $\varepsilon = 0.62$). The interaction between epoch and trial type did not withstand this ANOVA ($F < 1, f = 0.22$). There was no main effect of trial type ($F(1, 19) = 1.44, p = 0.245, f = 0.27$) neither a main effect of epoch ($F(2.95, 55.97) = 1.12, p = 0.350, f = 0.24$). **Table 3.5** shows the means and standard deviations for the mean number of visits, for each epoch and trial type.

Table 3.5 Means and standard deviations for the number of visits overall and for each trial type, for all epochs.

	Epoch 1	**Epoch 2**	**Epoch 3**	**Epoch 4**	**Epoch 5**	**Epoch 6**
Cued trials	*M* = 7.16 *SD* = 2.35	*M* = 6.54 *SD* = 2.09	*M* = 6.36 *SD* = 2.52	*M* = 6.39 *SD* = 2.43	*M* = 6.05 *SD* = 2.45	*M* = 6.33 *SD* = 2.24
Uncued trials	*M* = 7.88 *SD* = 3.09	*M* = 7.11 *SD* = 3.58	*M* = 6.52 *SD* = 2.89	*M* = 7.83 *SD* = 2.88	*M* = 7.65 *SD* = 6.92	*M* = 9.13 *SD* = 6.15
Overall	*M* = 7.52 *SD* = 2.73	*M* = 6.83 *SD* = 2.91	*M* = 6.44 *SD* = 2.68	*M* = 7.11 *SD* = 2.73	*M* = 6.85 *SD* = 5.18	*M* = 7.73 *SD* = 4.78

3.3.2.2 Individual differences

Post-Experiment Questions

Coding of these questions was the same as Experiment 1A. Out of 20 participants, 95% reported using a strategy to find the target, of which a binomial test confirmed that this was above 50% chance level ($p < 0.001$). When the participants who confirmed using a strategy were asked to explain it, 15% responded with some acknowledgement of the target's location or the cued sides of space (*binomial*, $p = 0.003$). For Question 2, 95% of participants said they had no sense of the target's location (*binomial*, $p < 0.001$). The one participant who said they had a sense, also demonstrated awareness of the probability cue in their answer (100%; *binomial*, $p < 0.001$). Finally, for Question 3, 85% of participants accurately identified the target's location when presented with a forced-choice. A binomial test demonstrated that this was above chance level, with a higher percentage of participants accurately identifying the cued side than not ($p = 0.003$). Results are summarised in **Table 3.6**.

Table 3.6 Experiment 1B - Post-Experiment Questions. Behaviourally probability cueing was attenuated, but participants still expressed some knowledge of the target's location when questioned. $*p < 0.05$, $**p \leq 0.001$.

Question	Answer	Binomial result
1A - Strategy *"Did you use a strategy to search for the target in the environment"*	Yes: 95% (*n* = 19) No: 5% (*n* = 1)	***p* < 0.001****, in the direction of more participants reporting a strategy.
1B - Strategy *"If YES please explain your strategy"*	Awareness: 15% (*n* = 3) No awareness: 85% (*n* =17)	***p* = 0.003***, in the direction of no awareness of the probability cue.
2A - Sense *"Did you have a sense of where the target was most likely to be in the environment?"*	Yes: 5% (*n* = 1) No: 95% (*n* = 19)	***p* < 0.001****, in the direction of no 'sense' of the targets location.
2B – Sense *"If YES please explain your 'sense' of the target's location"*	Awareness: 5% (*n* = 1) No awareness: 95% (*n* = 19)	***p* < 0.001****, in the direction of no awareness of the probability cue.
3 - Final probe *"If I told you that the target was more likely to appear on one side, would you be able to guess which one?"*	Correct judgement: 85% (*n* = 17) Incorrect judgement: 15% (*n* = 3)	***p* = 0.003***, more participants correctly identified the cued side.

Questionnaire data

Cueing effect measures for all dependent variables, whether they showed significance in the behavioural results or not, were calculated in the same way as detailed in Experiment 1A[6]. These were entered in correlational analysis alongside the questionnaire data. As with Experiment 1A, there were significant, positive

[6] Although the analysis was conducted using epochs of data (10 trials per epoch), the cueing effects were calculated by separating the trials into two larger blocks of trials (30 trials per block).

relationships between all the cueing effect measures ($p < 0.001$). There was a negative significant relationship between gender and the cueing effect for the percentage first visits to the cued side (r_{pb}= -.45, $p = 0.047$). This indicated that males made fewer first visits to the cued side than females. On average, across the trial sequence, 38.54% (SD = 29.05) of first visits were directed towards the cued side if the participant was male, in comparison to females that committed 70.70% (SD = 35.38) of first visits towards the cued side. All other correlations between gender, SBSODS, EHI, gaming hours and the cueing effects did not reach significance ($p > 0.05$). The results from all correlations are in **Table 3.7.**

Table 3.7 Experiment 1B - Pearson's Product-Moment Correlations (r and α) and a Point-Biserial Correlation (r_{pb} and α) for the cueing effect and questionnaire measures, $*p < 0.05$, $**p \leq 0.001$.

		1.	2.	3.	4.	5.	6.	7.	8.
1. Search cueing effect		-							
2. First visits cueing effect	*r*	**.89****	-						
	α	**< 0.001**							
3. Density cueing effect	*r*	**.93****	**.98****	-					
	α	**< 0.001**	**< 0.001**						
4. Number of visits cueing effect	*r*	**.95****	**.91****	**.95****	-				
	α	**< 0.001**	**< 0.001**	**< 0.001**					
5. EHI	*r*	.09	.09	.09	.07	-			
	α	0.696	0.715	0.703	0.775				
6. SBSODS	*r*	-.03	-.04	-.06	.10	.15	-		
	α	0.908	0.883	0.804	0.681	0.525			
7. Gaming hours	*r*	-.05	.11	.13	.06	.31	.15	-	
	α	0.823	0.658	0.580	0.800	0.188	0.521		
8. Gender	r_{pb}	-.33	**-.45***	-.41	-.30	.26	.31	.27	-
	α	0.163	**0.047**	0.076	0.205	0.266	0.178	0.248	

3.3.3 Discussion

In Experiment 1B, a probability cueing paradigm was designed in which learning over the trial sequence could be analysed more closely than in the preceding experiment. Within every 10 trials, two uncued trials randomly occurred amongst eight cued trials. Probability cueing was examined by separating the trials into smaller epochs of 10 trials.

Unlike Experiment 1A, probability cueing effects were not consistently evident across all measures. There were no effects of trial type for search time, first visits or the number of visits. However, there was a significant effect of density, with a greater percentage of visits to the cued side of space. Density did not, however, change across the epochs, suggesting that participants began visiting cued locations more than chance level early on, and consistently stuck with this strategy. Overall, these behavioural results suggest that probability cueing was relatively weak when the trials were pseudo-randomised.

Although behavioural results demonstrated minimal probability cueing, Post-Experiment Questions revealed a slightly different scenario. In comparison to Experiment 1A in which successful probability cueing was found, a higher percentage of participants in this current experiment reported using a strategy, with 19 out of 20 (95%) of them expressing a strategic approach to their searches. This was in comparison to 15 out of 20 (75%) participants in Experiment 1A. Similarly, to Experiment 1A, when participants were probed further about their strategies few demonstrated awareness of the cue (Experiment 1A: 20%; Experiment 1B: 15%). For

the final question, many participants could accurately guess the cued side (85%), and this result was statistically significant above chance level. It is striking that participants expressed some form of awareness of the cue, yet did not modulate their searches as appropriate.

It is not clear why probability cueing was stronger in Experiment 1A than in Experiment 1B. These differences may be due to the type of reward that subjects were receiving for their participation which may have influenced their motivational state. In Experiment 1A, participants received a monetary reward, and they were recruited from a variety of degree courses at the University of Nottingham. In contrast, in Experiment 1B, all participants were within their first year of studying for their Psychology degree, and were rewarded a course credit for their participation. This has no monetary value, and, although not a mandatory part of their course, students are encouraged to collect these credits for a module.

The differences in reward across the two experiments may have led to differences in attention allocation. A study by Stankevich and Geng (2014) directly investigated the effects of reward and probability. Importantly, they found that when a reward was present, the RT benefits were greater for targets appearing on the high probability side, whereas this effect was attenuated when a reward was absent. This emphasises the possibility of an additive relationship between probability and reward, with strong rewards and high spatial probabilities working in conjunction to bias attention more than they do independently. The null reward associated with finding the target in Experiment 1B may have affected the amount of effort and attention the participants were putting into the task. The lack of reward may have affected their

motivation, and therefore their ability to effectively learn. Other research has also suggested that a lack of monetary reward can decrease performance (e.g. Lansdown & Saunders, 2012). For all further studies, a monetary reward (but of varying value depending on the time length of the experiment) was offered to rule out this possibility.

Another reason why probability cueing may not have occurred in Experiment 1B is that the trial structure may have been more difficult to learn. For example, it could be that randomly ordering trials helps to bias attention because more cued trials tend to occur together. This is similar to inter-trial repetition priming (Maljkovic & Nakayama, 1996) in which repetitions of a target's *specific location* (not trial type) can improve RT performance. In the case of Experiment 1B, although the uncued trials appeared randomly within 10 trials, this may have inadvertently induced a 'structured' order that disadvantaged learning.

A final reason why there were differences in results for Experiment 1A and 1B may be due to the individuals' personal experience of simulator sickness. A recent study by Maraj, Badillo-Urquiola, Martinez, Stevens and Maxwell (2017) found a very complex relationship between engagement, simulator sickness and effectiveness of learning. Specifically, they found that as an individual's perceived sense of engagement in a task increased, their degree of reported simulator sickness decreased, which in turn had a positive effect on learning. High engagement in a task leads to increased motivation to complete the task to the best ability, which work together to promote effective learning. It could be that although the drop-out rates in Experiment 1A were higher (n = 3) than drop-out rates for Experiment 1B (n = 2), the final

participant sample used in Experiment 1B may have experienced more simulator sickness than those in Experiment 1A. This may particularly be the case as slightly more females were recruited in Experiment 1B (n = 13) than in Experiment 1A (n = 10), and females tend to experience simulator sickness at a greater level than males (Biocca, 1992). However, this data is unknown as simulator sickness ratings were not monitored in either experiment.

In the following experiment the immersive qualities of the environment were enhanced to examine whether efficient probability cueing could be reproduced within a larger-scale, immersive VE. Previous research has suggested that enhancing the display size can have a positive effect on learning and performance in spatial tasks especially in comparison to desktop displays (Tan et al., 2006). Increasing the display size immerses users more in the world, enhancing presence (Prothero & Hoffman, 1995), allowing participants to adopt more efficient strategies to solve problems and gain better memory from learned information (Tan et al., 2006). This is one of the reasons why modern simulator training is more likely to take place in immersive environments (Tarr & Warren, 2002) rather than virtual worlds displayed on desktop monitors, as used in Experiment 1. These immersive environments can range from large-scale simulators such as driving (e.g. Foy, Runham, & Chapman, 2016) or pilot simulators (e.g. van de Merwe, van Dijk, & Zon, 2012) to smaller-scale, yet still immersive, environments such as projected screens (e.g. Cruz-Neira, Sandin, & Defanti, 1993) or HMDs (e.g. Ruddle & Lessels, 2009).

3.4 Experiment 2: Probability cueing in immersive space

In Experiment 2, the immersive qualities of the VE were enhanced. As before, participants were told to search for a spatially manipulated, hidden target as quickly as possible within the virtual arena. It was predicted that probability cueing would occur, and that its overall effect size may even be superior to Experiment 1A, as the task's immersive quality had improved. One reason why this may occur is because of gains in the FOV, in comparison to smaller display sizes, created by casting a larger retinal image of the environment (Tan et al., 2006). Previous studies have found that participants who are exposed to environments with wider FOVs, are more likely to conduct 'perfect' searches, by making fewer revisits, spending less time planning, less time stationary and more time travelling (Lessels & Ruddle, 2004; Pingel & Schinazi, 2014; Thomas et al., 2006). In turn, this not only enhances immersion but can also increase feelings of presence (Lin, Duh, Parker, Abi-Rached, & Furness, 2002). If a stronger feeling of presence does occur, this could ultimately induce the formation of explicit probability cueing strategies, in comparison to Experiment 1A where implicit strategies dominated.

The original aim of this experiment was to keep the VE identical to that of Experiment 1. However, initial piloting revealed that the textured surfaces, high speed of rotation, and the number of trials, contributed towards increased levels of simulator sickness. These factors have been shown to increase the risk of unpleasant feelings in other VE studies (e.g. Jaeger & Mourant, 2001). Therefore, these parameters were adapted to take these issues into account (detailed in **Section 3.4.1**).

At three time-points during Experiment 2, participants were asked to rate their current feelings of associated simulator sickness symptoms using the Simulator Sickness Questionnaire (SSQ: Kennedy et al., 1993). It has been shown that immersive VEs can induce increased feelings of sickness (Sharples et al., 2007) hence the questionnaire was used in this experiment. Simulator sickness can cause high drop-out rates in experiments (Biocca, 1992), and may cause attention and engagement to dwindle when symptoms worsen (Maraj et al., 2017). Thus, it was predicted that those who reported low levels of sickness would be more sensitive to probability cueing, in comparison to those who reported high levels of simulator sickness. To investigate this, simulator sickness sub-scales were added into the correlations with the questionnaire data (EHI, SBSODS, gaming hours, gender) and cueing effect measures.

3.4.1 Method

3.4.1.1 Participants

20 participants were recruited from the University of Nottingham (14 females); in total, 25 participants were recruited but five dropped out due to feelings of simulator sickness. The age of the participants ranged from 20 to 27 years (M = 22.50; SD = 1.99). All participants had normal to corrected normal vision and, as recorded by the EHI, all were right handed (M = 89.50; SD = 16.38). Subjects had not participated in any other probability cueing studies (such as Experiment 1). Potential participants were unable to continue with recruitment if they: had a history of simulator or motion sickness, were susceptible to migraines, dizziness or blurred

vision, or if they had epilepsy. These factors have previously been associated with increased simulator sickness levels (Ruddle, 2004; Cobb et al., 1999). As with Experiment 1, each participant was randomly assigned an array combination, from 1 to 20, which corresponded to a unique set of search locations. Participants were offered £4 in exchange for their time.

3.4.1.2 Materials

The VE

The VE was displayed using three Barco F22 series colour projectors (1920x1200 resolution). These projectors displayed the environment onto a 180° circular projector screen (5m in diameter), sub-tending 180° of visual field (see **Figure 3.7**). The VE outlined in Experiment 1A (**Section 3.2.1.2**) was also used in this experiment, except for some changes, primarily to the visual features. Textures on the floor and walls were replaced with solid colours. A solid dark grey colour (RGB: 178, 178, 178) was applied to the floor and the four walls of the arena were solid colours of yellow (RGB: 255, 255, 0) and blue (RGB: 0, 0, 255). Rotational speed was reduced by half. Other than these factors, the properties of the environment and the participants' movement through it were the same as the preceding experiments.

As in Experiment 1A, a non-identifiable target was located under one of the 12 search items per trial. Piloting suggested that it was difficult for the computer to register the target area on the larger screen dimensions, hence the X and Y coordinates of the target area was increased by 0.10 maze units. Participants were also

told in the initial instructions to ensure that they lined their movement centrally with each item and "walked" directly over the top, to avoid miscalculation.

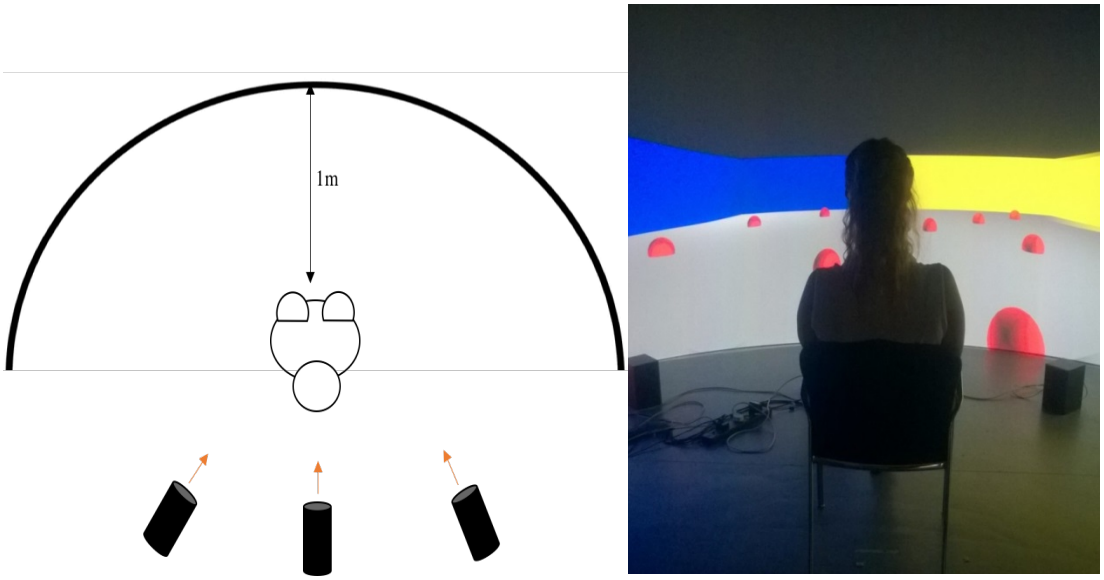


Figure 3.7 Experiment 2 set-up. *Left*: Schematic diagram of the environment. Cylinders represent coloured projectors. *Right*: Participants view of the environment.

Trials from Block 1 per combination were used, as the trial number was reduced so that 30 trials were untaken rather than 60 trials, to reduce simulator sickness. The trials were defined by the cued and uncued sides of space (80%;20%), and the trial order was the same as Experiment 1A, with the trial types appearing in a random order (apart from consecutive target location repetitions that were absent). The cued side (left, right) and the start position (north, south) was counterbalanced.

Monitoring simulator sickness

For the SSQ, the participant was required to rate how they 'currently felt' for a variety of statements. They scored these statements based on feeling: 'none', 'slight', 'moderate' or 'severe'. Although this did not occur, participants were aware that if they ticked any statements as 'moderate' or 'severe' at the beginning of the experiment, they would not be allowed to take part and would have to rearrange with the Experimenter. This was to stop this feeling from being exacerbated by the VE.

3.4.1.3 Procedure

After signing a Consent Form, and before the task began, participants completed a copy of the SSQ. Participants were then seated centrally, 1m away from the screen. Participants were instructed to the "find target as quickly as possible". As in Experiment 1, two practice trials were firstly completed using a wireless keyboard, in order to familiarise the participant with the controls and the VE. All button responses (arrow keys) were the same as Experiment 1. Once complete, participants were asked to fill in another copy of the SSQ. If any statements were ticked as 'moderate' or 'severe', then the experiment was terminated. The participant then completed the probability cueing trials.

After completing the trials, participants' awareness of probability cueing was probed using the same method as Experiment 1B (i.e. with Question 2B included). Participants were then asked, on average, how many hours they spent a week playing computerised games. Finally, participants completed the SBSODS, the EHI, another

SSQ and a Post-Experiment Checklist in which they agreed to not drive for 30 minutes after the experiment (due to safety and ethical reasons) and agreed that any sickness symptoms had subsided. It was decided that these questionnaires would be answered finally, after the experimental task, so that participants were completely blind to the aims and were less likely to question what the experiment was measuring. The whole experiment lasted approximately 40 minutes.

3.4.2 Results

Each dependent variable was processed and analysed using *t*-tests. 2.33% of data was pre-processed for erroneous revisits.

3.4.2.1 Behavioural results

Search time

Median search time to the cued and uncued sides of space were examined. Participants were numerically quicker to find the target when it was on the cued side of space (M = 22.71s, SD = 9.22) in comparison to the uncued side (M = 30.25s, SD = 15.98). However, a paired samples *t*-test demonstrated that this difference was not significant ($t(19) = -1.74$, $p = 0.097$. $d_z = 0.39$).

First visits

On average, 65.33% (SD = 25.12) of first visits were directed towards the cued side of space. A one sample *t*-test showed this to be significantly above chance

($t(19) = 2.73$, $p = 0.013$, $d = 0.61$). This suggests that participants were efficient in their search, by directing their initial visit towards the cued side.

Density

Another one sample *t*-test was conducted to examine whether the density of visits was reliably greater to the cued side of space. On average, density was 65.22% ($SD = 14.96$). This was significant ($t(19) = 4.55$, $p < 0.001$, $d = 0.83$), suggesting that participants were consistently visiting the cued side of space more than chance level.

Number of visits

On average, numerically more visits were made on uncued trials ($M = 9.72$, $SD = 4.14$) than cued trials ($M = 8.23$, $SD = 2.84$). However, this difference was not statistically different ($t(19) = -1.25$, $p = 0.225$, $d_z = 0.28$) suggesting that a bias in the number of visits made across the two trial types did not occur.

3.4.2.2 Individual differences

Post-Experiment Questions

Post-Experiment Questions were scored in the same way as Experiment 1B. 85% of participants of reported using a strategy to find the target. This was significantly above chancel level (*binomial*, $p = 0.003$). Of this number, 55% of participants reported some awareness of the target's location when asked to further explain what strategy they used, however this was not significantly above chance level (*binomial*, $p = 0.824$). 35% of participants reported 'having a sense' of the

target's location, but again, this was not significantly above chance level (*binomial*, $p = 0.263$). When this pool of participants was probed further, 20% of those mentioned the target's location or the cued side of space (*binomial*, $p = 0.012$).

Finally, when presented with a forced-choice, all 20 participants (100%) correctly identified the side of space that was cued (*binomial*, $p < 0.001$). The results are shown in **Table 3.8.**

Table 3.8 Experiment 2 - Post-Experiment Questions. Behaviourally probability cueing was attenuated, but participants still expressed some knowledge of the target's location when questioned. *$p < 0.05$, **$p \leq 0.001$.

Question	Answer	Binomial result
1A - Strategy *"Did you use a strategy to search for the target in the environment"*	Yes: 85% ($n = 17$)	***p* = 0.003***, in the direction of more participants reporting a strategy.
	No: 15% ($n = 3$)	
1B - Strategy *"If YES please explain your strategy"*	Awareness: 55% ($n = 11$)	$p = 0.824$, less than 50% chance level.
	No awareness: 45% ($n = 9$)	
2A - Sense *"Did you have a sense of where the target was most likely to be in the environment?"*	Yes: 35% ($n = 7$)	$p = 0.263$, less than 50% chance level.
	No: 65% ($n = 13$)	
2B – Sense *"If YES please explain your 'sense' of the target's location"*	Awareness: 20% ($n = 4$)	***p* = 0.012***, in the direction of no awareness of the probability cue.
	No awareness: 80% ($n = 16$)	
3 - Final probe *"If I told you that the target was more likely to appear on one side, would you be able to guess which one?"*	Correct judgement: 100% ($n = 20$)	***p* < 0.001****, more participants correctly identified the cued side.
	Incorrect judgement: 0% ($n = 0$)	

SSQ data

The SSQ has three sub-score categories: nausea, oculomotor-related and disorientation (Kennedy et al., 1993). **Table 3.9** outlines each symptom within these categories, as well the mean ratings across participants. Participants rated each of the symptoms as either "none" (scored as 1); "slight" (scored as 2); "moderate" (scored as 3); or "severe" (scored as 4). The mean score per category per participant, was then entered in a repeated measures ANOVA with *sub-score* (three levels: nausea, oculomotor-related, disorientation) and *rating time-point* (three levels: time-point 1 [before the experiment began], time-point 2 [after the practice trials], time-point 3 [at the end of the experiment]) as factors. Both factors and the interaction were significant at Mauchley's test, indicating that they violated sphericity (time-point: $\chi^2(2) = 7.87$, $p = 0.020$; sub-score: $\chi^2(2) = 18.11$, $p < 0.001$; time-point x sub-score: $\chi^2(9) = 44.28$, $p < 0.001$). Degrees of freedom were adjusted using Greenhouse-Geisser estimates of sphericity for all effects reported using this ANOVA (time-point: $\varepsilon = 0.74$; sub-score: $\varepsilon = 0.61$; time-point x sub-score: $\varepsilon = 0.52$).

Table 3.9 Mean ratings of the SSQ for each sub-score at the beginning of the experiment (time-point 1), after the practice trials (time-point 2) and at the end of the experiment (time-point 3). Symptoms that form the sub-scores are detailed.

	Nausea General discomfort, increased salivation, sweating, nausea, difficulty concentrating, stomach awareness, burping.	**Oculomotor-related** General discomfort, fatigue, headache, eye strain, difficulty focusing, difficulty concentrating, blurred vision.	**Disorientation** Difficulty focusing, nausea, fullness of the head, blurred vision, dizziness (eyes open), dizziness (eyes closed), vertigo.
Time-point 1	$M = 1.04$; $SD = 0.19$	$M = 1.05$; $SD = 0.22$	$M = 1.02$, $SD = 0.09$
Time-point 2	$M = 0.99$, $SD = 0.29$	$M = 1.04$; $SD = 0.38$	$M = 0.97$, $SD = 0.27$
Time-point 3	$M = 1.12$, $SD = 0.35$	$M = 1.18$, $SD = 0.40$	$M = 1.09$; $SD = 0.29$
Overall	$M = 1.05$, $SD = 0.19$	$M = 1.09$, $SD = 0.24$	$M = 1.09$, $SD = 0.24$

This ANOVA showed a significant main effect of simulator sickness levels across the three time-points ($F(1.48, 28.06) = 4.21$, $p = 0.035$, $f = 0.47$). Post-hoc Bonferroni-corrected Pairwise Comparisons demonstrated that ratings at time-point 1 ($M = 1.03$ $SD = 0.08$) were significantly lower ($p = 0.012$) in comparison to time-point 3 ($M = 1.31$, $SD = 0.16$). However, ratings at time-point 2 ($M = 1.00$, $SD = 0.25$) did not differ from time-point 1 ($p = 0.067$) or time-point 3 ($p > 1.00$). The main effect of sub-score ($F(1.22, 23.25) = 3.71$, $p = 0.059$, $f = 0.44$) was not significant, as well as the interaction effect between sub-score and rating time-point ($F < 1$, $f = 0.04$).

Questionnaire data

Cueing effect measures were calculated for all variables. As there was only one block of trials, the cueing effects were derived slightly differently. For search time and the number of visits, the difference between both measures on cued and

uncued trials was calculated as the cueing effect. For density and first visits, the 'raw' percentage scores were entered. These cueing scores were entered in correlational analyses with the questionnaire data and the mean ratings for each of the sub-scores in the SSQ.

Results from the correlations are shown in **Table 3.10**. There were significant, positive relationships between all the cueing effects ($p < 0.05$). All three sub-scores from the SSQ were also positively related, suggesting that scoring highly on one of the sub-scores also meant scoring highly on the other two ($p < 0.05$). Finally, there was a statistically significant positive relationship between SSQ oculomotor-related sub-score and first visits ($r = .47$, $p = 0.036$) suggesting that more first visits to the cued side induced greater oculomotor difficulties. This positive relationship was also replicated for first visits and SSQ disorientation sub-score ($r = .48$, $p = 0.032$). There was also a near-significant, positive relationship between SSQ disorientation sub-score and density ($r = .42$, $p = 0.067$). All other analyses did not reach significance ($p > 0.05$).

Table 3.10 Experiment 2 - Pearson's Product-Moment Correlations (r and α) and a Point-Biserial Correlation (r_{pb} and α) for the cueing effect and questionnaire measures, $^{*}p < 0.05$, $^{**}p \leq 0.001$.

		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
1. Search cueing effect		-											
2. First visits cueing effect	*r*	**.70 ****	-										
	α	**0.001**											
3. Density cueing effect	*r*	**.82 ****	**.92 ****	-									
	α	**< 0.001**	**< 0.001**										
4. Number of visits cueing effect	*r*	**.84 ****	**.57 ***	**.67 ****	-								
	α	**< 0.001**	**0.009**	**0.001**									
5. EHI	*r*	.10	.03	-.01	.22	-							
	α	0.689	0.906	0.975	0.350								
6. SBSODS	*r*	-.18	.11	< .01	-.29	-.30	-						
	α	0.458	0.649	0.992	0.231	0.200							
7. Gaming hours	*r*	-.15	-.27	-.14	-.02	-.34	-.24	-					
	α	0.538	0.243	0.551	0.934	0.139	0.301						
8. SSQ nausea	*r*	.21	.37	.26	-.04	.09	.42	-.11	-				
	α	0.369	0.107	0.274	0.870	.699	0.066	0.652					
9. SSQ oculomotor	*r*	.24	**.47 ***	.28	-.04	.20	.26	-.25	**.85 ****	-			
	α	0.316	**0.036**	0.233	0.856	0.396	0.261	0.293	**< 0.001**				

10. SSQ disorientation	*r*	.33	**.48 ***	.42	.21	.10	.33	-0.02	**.88 ****	**.70 ****	-	
	α	0.156	**0.032**	0.067	0.376	0.682	0.151	0.927	**< 0.001**	**0.001**		
11. Gender	r_{pb}	.37	.38	.26	.28	-.12	-.27	-40	0.04	.17	.05	-
	α	0.108	0.098	0.262	0.232	0.626	0.249	0.082	0.858	0.469	0.827	

3.4.3 Discussion

In this experiment, a VE was used to investigate probability cueing in an immersive context. Akin to Experiment 1, participants were required to search for a target item that, unknowingly to them, appeared more frequently on one side of space than the other. The VE was displayed using a large projected screen, rather than a monitor, to enhance the immersive properties of the task. Against predictions, probability cueing in this experiment was weak, with only density and first visits showing significant effects. Search time was not faster, nor were there fewer inspections, on cued trials in comparison to uncued trials. Contrastingly, participants accurately identified the cued side of space during post-experiment questioning, with 100% (20 out of 20) of guesses being accurate, even though behaviourally participants did not bias their search. This results mirrors those of Experiment 1B where behaviourally probability cueing was attenuated but upon probing, some expression of the cue was found.

One issue that was anecdotally reported by some participants during the experiment was difficulties using the controls. As mentioned in the procedure, the programmed target regions were increased slightly to accommodate for, what seemed to be, a slight mismatch between the visuals being projected and the movement. Although this was corrected for with pre-processing of the data, it may still have been the case that the trials that were in the analysis had some erroneous revisits. Furthermore, during the experiment, the trial still needed to be completed and the target may have been missed on more than one occasion. This could have had a

detrimental effect on learning by interfering and potentially even causing participants to avoid a specific location on future trials. Research has suggested that the addition of audio, can increase self-reported presence and memory of VEs (Dinh, Walker, Song, Kobayashi, & Hodges, 1999). Therefore, in the next VE experiment audio was added so that the participants had feedback to confirm their visits.

This issue also highlights that there may be a trade-off between immersive technology and its utility. This is especially problematic when considering that simulator training tends to be conducted in similar types of immersive environments to the one used in this experiment; this trained behaviour is then later thought to transfer to the real-world (Tarr & Warren, 2002; Waller et al., 1998). If users find handling and manipulating movements in the VE difficult due to technological glitches, not only can the tasks utility be affected but also the learnt behaviour (Ruddle, 2001). Further to this point, it has been demonstrated that lags or delays in VE systems, can encourage participants to experience and report high levels of simulator sickness (Ruddle, 2004). The present experiment received the highest drop-out rate due to sickness levels, compared to other experiments reported so far (Experiment 1A: $n = 3$; Experiment 1B: $n = 2$; Experiment 2: $n = 5$). This again emphasises the potential trade-off between immersive technology and its utility.

A positive relationship between first visits to the cued side and two sub-categories (disorientation and oculomotor difficulties) of the SSQ were found. High levels of simulator sickness may have occurred because of the difficulty some participants had with the controls, incurring increases in erroneous re-inspections. However, considering these were corrected for before data analysis, this correlational

result contrasts with research by Maraj et al. (2017) who found that lower self-reported simulator sickness scores were related to efficient learning and engagement in a task. The two significant correlations found in this current experiment suggest the opposite, in that higher scores on the SSQ correlated with more efficient first visit behaviour.

The underlying reason for this result is ambiguous. However, it is important to consider that other behavioural measures did not correlate with any SSQ sub-scores, and an increase in overall ratings of simulator sickness at the end in comparison to the beginning of experiment was found. These results highlight that, overall, probability cueing was weak and that sickness levels increased over time. This instead suggests that an increase in sickness from beginning to the end of the experiment may have affected engagement, decreasing levels of focus and attention, and, in turn, meaning learning was unlikely to be proficient. This theory would be in line with the work by Maraj et al. (2017) but motivation and simulator sickness would need to be measured more accurately in future experiments.

An explanation for the lack of probability cueing in this experiment lies in the rate at which spatial learning may occur. It has been shown that spatial learning occurs slower in virtual space than it does in real space (Waller et al., 1998), for example, high error rates in distance and accuracy estimations (Sinai, Krebs, Darken, Rowland, & McCarley, 1999) and general navigational struggles such as disorientation (Kirschen et al., 2000). A study by Ruddle (2001) found that the learning rate of participants that experienced frequent and timely exposures (several hours) in a virtual corridor task was variable. Some participants immediately formed

near-perfect knowledge of the environment whilst others remained disoriented and consistently made errors. They also found very similar results when participants were asked to search for target's in a large VE consisting of 16 rooms, with some participants repeatedly searching the same area. The author suggests that participants struggled to remember the paths which they had taken previously and learn their route as they travelled through the VE. Some participants in this current experiment may have engaged in similar repetitive behaviour, in turn disorienting themselves, slowing their rate of spatial learning and the probability cue.

Despite this, the task in the current experiment was practically identical to that of Experiment 1A in which probability cueing was observed. It has previously been shown that learning in highly immersive display systems, such as large projected screens, is superior to that of small-scale displays (Patrick et al., 2000; Tan et al., 2006). Some studies instead suggest that there is no difference in spatial learning between immersive display types, such as HMDs, and desktop monitors (Ruddle & Lessels, 2009; Ruddle, Payne, & Jones, 1999; Waller et al., 1998). Even so, this previous research suggests that spatial learning is either at its worst when a desktop VE is used or develops in the same way in desktop and immersive displays. Taking this into account, it is striking that no effect for Experiment 2 was found.

It is, however, important to note that the environment in the present experiment was stripped of some detailed visual aspects that may have aided search, such as texture (Lessels & Ruddle, 2004; Vinson, 1999). It has been shown that additional textures can help participants to remember object and building locations (Kirschen et al., 2000; Vinson, 1999), hence removing the brick, fence and grass

textures may have been detrimental to probability cueing in this experiment. This theory is discussed further in **Section 3.6**.

Since changing the nature of the environment and the display medium appeared to attenuate probability cueing in Experiment 2, compared to Experiment 1A, the following experiment examined probability cueing in a 3D space involving full-body search. Compared to the VE, this environment was a 'real', 3D space, in a laboratory room, and search involved full-body movement and physical effort. It has been suggested that this type of search is comparable to foraging, as it involves similar properties, such as actively deciding where to direct efforts, to save time and energy, in a dynamic environment where predictions are made that encompass the perceived likelihood of success (i.e. finding the target) (Gilchrist et al., 2001; Smith et al., 2010). On the other hand, some researchers have argued that visual search tasks provide strong evidence of foraging-type search behaviours (e.g. Gilchrist et al., 2001; Jiang et al., 2016; Smith et al., 2010), despite the clear difference in spatial scale and task demands between visual and naturalistic search tasks (Smith et al., 2010). The aim of Experiment 3 was to use a similar set-up to the large-scale foraging apparatus used by Smith et al. (2010) to replicate the probability cueing results that they reported in Experiment 2 of their large-scale research.

3.5 Experiment 3: Probability cueing in full-body search

Experiment 3 investigated probability cueing in a laboratory set-up. Smith et al. (2010) were the first researchers to demonstrate probability cueing in real space. The search environment consisted of a large hexagonal room with curtained 'walls',

devoid of landmarks, and several LED lights positioned in an array on the floor. Participants' were instructed to search for a target, indicated by a colour change upon it being pressed. They found that participants only learnt the probability cue when their start position was held constant throughout the trial sequence (i.e. they always started from the north) and when the array on the floor was also held constant throughout the trials (i.e. the array did not change per trial akin to visual search). Unlike visual search studies (e.g. Geng & Berhmann, 2002), participants expressed conscious awareness of the cue. The physical effort and movement necessary for task completion may bring learning to the forefront of conscious awareness as spending time and physical effort searching an area that is known to be less fruitful is inefficient.

The basic design for Experiment 3 was the same as Experiment 2 in the Smith et al. (2010) research. Participants were required to search for a target amongst several LED lights on the floor. Their start position and the array stayed constant throughout the experiment to encourage probability cueing and ensure egocentric and allocentric coordinates were invariable. Unbeknownst to the participants, the target was manipulated to appear more frequently on one side of space than the other. It was predicted that probability cueing would be successful, with participants actively biasing their search towards the cued side of space. The large-scale space differed to the environment used by Smith et al. (2010) on a few minor factors including: the total search items presented and the shape and size of the environment. The array size was reduced to 12 items (rather than 16 items), to be in line with the amount of search items in the VE studies previously conducted. The environment was rectangular

(rather than hexagonal) and had slightly smaller dimensions (4m x 2m) due to space restrictions.

The main purpose of replicating the aforementioned research and establishing probability cueing in this laboratory set-up was so that, if successful, the environment could later be used to examine the transfer of probability cueing between virtual and real space. That experiment is detailed in **Chapter 4**. The environment was, therefore, also designed to be similar in nature to the VE, for example, by having search items on the floor of the environment that the user interacted with. The array combinations of the search items were also consistent with the arrays used in the previous studies, for example, participant X in this experiment may have experienced the same array as participant Y in Experiment 1A.

Additionally, during the trials, participants were asked to wear eye tracking glasses. These were used for two reasons: as a camera to capture search paths and to measure where on the floor participants were looking before they began their search. This would not be the first study to examine eye movements during probability cueing, but is the first to examine eye movements in a 3D context. Walthew and Gilchrist (2006) and Jones and Kaschak (2012) found conflicting conclusions during their experiments that examined visual search. The latter researchers suggested that participants took a global approach, consistently directing their first saccade to the cued side no matter whether the target was cued or uncued, whilst the former suggested that first saccades were only directed to the cued side when the target had previously been located on that specific side. It is unknown what strategy is adopted under a 3D context.

A study by Won, Lee, and Jiang (2015) examined the direction of the first head movement during a search task that was large-scale but involved no physical movement. Participants were instructed to make a button press every time they found a coin that was located on the floor of an outdoor space. No movement was required; the task was visual search only, but conducted in an outdoor space rather than on a computer screen. Participants completed a training phase in which the target was manipulated to appear more frequently (50%) in one quadrant in comparison to three others (16.70% each). In the testing phase, the target's location probability was either maintained or changed to be even across all quadrants (25% in each). Participants showed a tendency to turn their heads towards the cued quadrant, although this tendency was independent of where the target was located on that specific trial. This is analogous to the conclusions drawn by Jones and Kaschak (2012) from a probability cueing task conducted under visual search constraints. Furthermore, Won et al. (2015) found that this tendency occurred even when the target was behind the participant, requiring them to search in the space behind their start position. They also found that during the testing phase, first head movements differed dependent upon whether the probability was maintained or changed. Participants in the 'probability maintained' group directed their first head movement towards the previously cued quadrant whereas participants in the 'probability changed' group demonstrated an absence of this bias. However, search times remained biased towards the previously cued quadrant in both groups. Thus, head movements rapidly adjusted to the environmental statistics, possibly as inaccurate movements were costly and effortful to make. Experiment 3 in this Thesis aims to build upon this, providing eye movement data from a large-scale search task.

For the Post-Experiment Questions, participants in this experiment (and all other experiments onwards, apart from Experiment 5) were asked to rate their answers on confidence scales. Verbal reports that probe awareness may be susceptible to response bias (Tunney & Shanks, 2003). For Questions 1 and 2, participants are asked to explain their answers, but in doing so, may set their own criterion or definitions of their search 'strategies' or their 'sense' of the targets location. This may lead to a claim of unconscious awareness, when in fact, they do possess a degree of awareness (Tunney & Shanks, 2003). This is demonstrated most effectively when considering Question 3 – in all experiments so far, participants could guess the cued side when told that one exists. Answers rated with high confidence may be reported by those of whom have set a more conservative response criterion, in comparison to those of whom have low confidence that may not, knowingly or unknowingly, even report it (Tunney & Shanks, 2003). Confidence ratings were scored from 1 (not confident at all) to 7 (extremely confident). A binary scale was chosen as it has been found previously that high confidence ratings scored on binary scales relate strongly to correct decisions (high accuracy), incurring less response bias, in comparison to continuous scales (i.e. scales that ask participants to rate from 50% to 100% accuracy) (Tunney, 2005; Tunney & Shanks, 2003). Confidence ratings for all questions were also included into the correlational analysis, for exploratory purposes.

For Experiment 3, it was predicted that participants would actively bias their search towards the cued side of space and express an awareness of the target's probable location. As with other experiments, search time, first visits, density and the number of visits were recorded. The aim was to analyse eye movements during a

three second countdown given to participants just before each trial began. Parallel to the results found by Won et al. (2015) and Jones and Kaschak (2012) it was hypothesised that saccades within this period of time would be biased towards the cued side, even if the target on the proceeding trial was not located in this hemispace. Participants would demonstrate this bias early in the trial sequence. This could be indicative of some form of planning before proceeding to search. Per trial, it was predicted that they would proceed to make a first visit to a search item within the cued side, with this search item being the one that they had just looked at.

3.5.1 Method

3.5.1.1 Participants

Originally, 22 participants were recruited from the University of Nottingham. Two participant data sets were excluded, as the eye tracker malfunctioned and the experiment was aborted. Therefore, 20 participants (14 female) were recruited for the final sample. From this experiment onwards, participants first language was recorded as a way of estimating any participants that may have struggled with the wording of the Post-Experiment Questions. Nine of these 20 participants reported English as their first language, but all were fluent English speakers. The age of the participants ranged from 18 to 33 years (M = 21.79, SD = 3.07). Participants who wore glasses for everyday activities (n = 8) were either asked to wear contact lenses on the day of the experiment or were asked to remove their glasses for the task. Two participants refused to do so, so wore the eye tracking glasses over the top of their normal glasses. Individuals were required to not have participated in any other probability cueing

experiments, be physically mobile and were told on the day of the experiment to wear non-restrictive clothing and to tie all long hair back so that the eye tracking camera consistently produced a clear video. One participant was left handed (EHI score: -90), whilst the 19 other participants were right handed (EHI scores: M = 77.63, SD = 18.44). Participants were paid £5 in exchange for their time.

3.5.1.2 Materials

The laboratory environment

The search environment was within a laboratory space. A diagram of this is in **Figure 3.8**. An area of 4m x 2m was allocated as the search area, on the floor of the laboratory. The floor was carpeted with dark tiles. The perimeter of the rectangle was surrounded by a white painted wall, apart from one short horizontal side (assuming a plan view, this would be the south side). This side was visibly cordoned off (using coloured tape) and a cross in the middle of this line indicated the start position for the participant in each trial. This side was the nearest to the door to allow the participant to easily exit the room. The start point was exactly half way across this line (at 1m). Unlike the VE studies, for all participants there was no counterbalancing of start positions, therefore no start positions were on the north side.

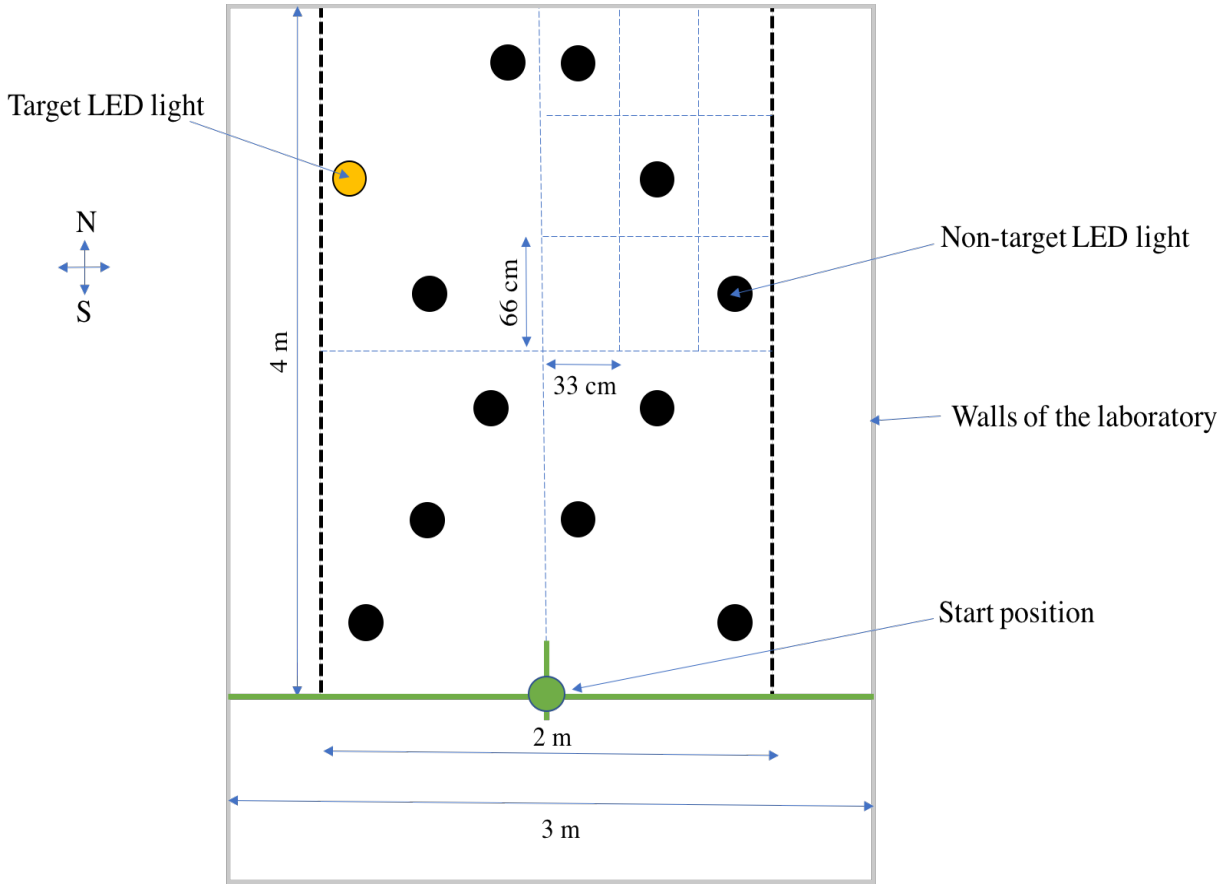


Figure 3.8 Plan view of the laboratory space. Dashed lines were not visible. Before activation, the target appeared visually the same as the other search items.

As in the VE, the environment was divided into four smaller quadrants (2m x 1m). Each of these quadrants were then divided again, into a 3x3 grid, with cells in this grid measuring 33cm x 66cm. Three search locations appeared in each of these quadrants with each positioned centrally within the smaller cells. The search locations were replicated, so that the search items in this experiment appeared in the same places as they did in the VE studies (for the design of these arrays, see **Section 2.1.3**). This meant that across the 20 participants, all 20 combinations that were designed for the VE experiment were replicated in this laboratory experiment.

At the beginning of each experiment, before the participant arrived, the 12 search locations were marked on the floor using chalk. They were positioned using a cardboard template, that approximately positioned the search locations within the centre (16.50cm x 33cm) of each of the smaller cells (33cm x 66cm). Once all 12 search locations were marked on the floor, they were covered using 12 button-press battery-operated LED lights, which represented the search locations akin to the red hemispheres in the VE. These lights were 6.50cm in diameter (dimensions: 8.20cm x 7.80cm x 7.60cm) and contained three bright white LEDs per unit. On the bottom of each of the lights was a sticky pad, which had Velcro centrally attached to it. This Velcro secured the light to the floor so that it stayed positioned on the chalk markings, even if it was accidently knocked. **Figure 3.9** demonstrates the lights on the floor of the laboratory space. The chalk was not visible to participants and was removed from the floor once the experiment had finished.



Figure 3.9 The laboratory space with a search array. The green tape marked the south of the space and the red tape marked the start position.

As with the VE studies, a non-identifiable target was located at one of the 12 search items on each trial. Only one of the LED lights could be illuminated upon activation (as the others did not contain batteries) – this represented the target, and its activation signalled the end of a trial. Participants were instructed to press each light using their fingertips. Participants used their dominant hand as it has previously been demonstrated that manipulating the motor dominance during large-scale search tasks, can have a detrimental effect on performance, increasing the task difficulty (Smith et

al., 2006). Thus, to control for such changes in difficulty, each participant was encouraged to use their dominant hand throughout the task.

At the beginning of each trial, the participant viewed all the LED lights switched off. Between trials, and once the participant had exited the room, the Experimenter picked up the battery-powered light (target) and switched it around with another light (non-target), so that the target was in a different location. The target appeared 80% of the time on one side of the environment (cued side) and 20% on the other (uncued side). Participants were unaware of the target location manipulation and were instructed to find the target "as quickly as possible". The same trial structure as Experiment 1A was used in this experiment; for example, for combination 1 in Experiment 1A the participant may have experienced target location 2, 4 then 6 for trials 1-3. This same sequence of trials was adhered to for combination 1 in this study. Again, the target never repeated in the same location across successive trials. The cued and uncued side of space was counterbalanced across participants. The direction participants faced on each trial was always frontwards (towards the search array) and always starting from the south side of the environment.

Eye tracking glasses

Participants were required to wear the Tobii Glasses 2 eye tracker system (see **Figure 3.10**). This system comprises of a pair of minimally intrusive, lightweight (45 grams) glasses, that were secured with an adjustable strap, tightened around the back of the participants' head. The glasses were then attached via a HDMI cable (connector on one of the arms of the glasses) to the recording unit – a small box that contained

several batteries and an SD card to record the live stream camera data. This box was secured onto the participants' waistband via a clip. A Dell laptop (running Windows 10) live-streamed footage from the scene camera on the glasses, via Tobii Pro Glasses 2 Controller Software, allowing the Experimenter to start and stop recordings for each trial. In total, 31 recordings were taken per participant; 30 for each of the experimental trials and one for the practice trial.



Figure 3.10 Tobii eyetracking glasses. Image not under copyright restrictions: *https://commons.wikimedia.org/wiki/File:Tobii_Glasses_2_Eye_Tracker_Wearable_System_Tobii_I.jpg*.

The glasses had one camera that faced away from the participants' face, positioned in the centre of the glasses, that recorded the outward visual scene. This scene camera recorded the live stream in H.264 video format, at a resolution of 1920 x 1080, at 25 frames per second, with a recording FOV of 82 degrees horizontally and

48 degrees vertically. The glasses also recorded audio with an integrated microphone. This camera had a slight latency of 300ms. The glasses also had four eye tracking sensors that were directed at the eyes (two per eye), recording at a sampling rate of 50Hz.

3.5.1.3 Procedure

Participants were firstly asked to sign a Consent Form, after which the eye-tacking glasses were set-up. If the participant was wearing glasses, they were asked to remove them. The eye-tracking glasses were then positioned, the head strap tightened and the recording unit attached to the participants' waistband. Calibration of the system involved standing approximately 1m away from a calibration card (a black circle with a small black dot in the middle of it) positioned on the wall. Participants were required to stare at this card until the software confirmed the calibration. This took about five seconds.

The experiment required two Experimenters; one in the search space, the other in an adjacent room, controlling the eye tracking calibration and checking the live stream recording. Once the calibration was complete, the participant was directed to join the other Experimenter in the search space. The participant firstly completed a practice trial, followed by 30 trials defined by the probability cue. At the beginning of each of these trials, the participant was told to stand centrally on the cross marked on the floor (i.e. the start position). Using a stopwatch, the Experimenter then gave the participant a three second countdown, followed by 'GO!', indicating that they could start their search. The three second countdown was there for two reasons: firstly, to

allow the Experimenter in the other room to ensure the live recording was working and, secondly, to later examine where on the floor participants were looking before they began their search.

All participants were told that the aim of the experiment was to find the light that illuminated when pressed (the target) as quickly as they could. If the light did not illuminate, they moved on and pressed another light of their choice until they found the target. Once the participant had found the target, they were asked to wait next to the light, until the Experimenter in the other room indicated that they had stopped the recording. The participant was then instructed to exit the search space and enter the other room for re-calibration of the eye tracker. Meanwhile, the other Experimenter switched the target light with a non-target light, so that the target was positioned in a different position for the next trial. The Experimenter had a checklist that they ticked off, along with a map of the environment, so they knew where to place the target per trial. Once this was complete, the eye tracker was re-calibrated and the next recording was started, the participant entered the search space and begun their search again after the three second countdown. The participant could have a break whenever they wished, as the task was physically tiring.

After all trials were complete, the participant completed the SBSODS and the EHI. They were then given the Post-Experiment Questions, with the confidence ratings. The participant was instructed to read each question individually, answer each at their own pace and to not go back and change any of answers. All questions remained the same, but each was followed by a confidence rating, from 1 (not confident at all) to 7 (extremely confident). Participants were then debriefed and were

required to sign a Post-Experiment Checklist, confirming that they felt physically well. The experiment lasted approximately 45 minutes.

3.5.2 Results

Eye tracking analysis

The live stream recording from the scene camera on the eye tracking glasses was imported and analysed using Tobii Glasses Analyzer. Initially, the eye tracking data from the first three second countdown was going to be analysed to allow for a richer understanding of probability cueing. However, upon reviewing this eye tracking data, many the recordings were obscured by the frame of the Tobii glasses. This meant that although the live scene camera was recording, the eye movements overlaid on the image were absent and therefore unable to be analysed. This also occurred if a participant moved their eyes below the sensors meaning their eyes were not in the recording FOV. Similarly, although participants were advised to tie any long hair back, some hair was in the way of the eye tracking cameras. The eye tracking data from the two participants who wore glasses underneath the Tobii Glasses were also absent because of the thick lenses. The calibration technique that the Tobii glasses require was also patchy at times, so eye movements were inconsistently mapped. Finally, some of the video files failed to record the three second countdown or even the trial in total due to technical glitches. In total, every participant had an issue with this eye tracking data. Therefore, this eye tracking analysis was disregarded.

The live recordings of the scene camera were manually coded. One Experimenter analysed five data sets and the other analysed 15. A coding system was created in Tobii Glasses Analyzer so that a specific key press on the keyboard represented an event in each video clip. Events included: three second countdown begin, three second countdown end (when the Experimenter said the word 'Go!') and each individual light press (12 in total). The recording start and end times were also noted. Each light was numbered within the combinations, and Experimenters coded each light press that the participant made on the trial, according this number. Each trial was coded from the participant's perspective. The Experimenter played each video clip and paused it when an event occurred. Each video clip was played with the sound; the sound added verification to the events, i.e. the Experimenter could be heard saying the three second countdown. The search measures (search time, first visits, density and the number of visits) were then calculated from this data. Each behavioural measure was analysed in SPSS software using *t*-test's.

To ensure search time was accurate, for each trial, the timestamp recorded at the end of the three seconds was noted, and subtracted from the timestamp at each visit thereafter. This was done to consider the extra time it took the participant to travel between the two testing rooms as well as the three second countdown.

One set of data was excluded from the analysis due to Experimenter error with the set-up of the trials. Therefore, all the data in the following analysis uses 19 data sets. Excluding the data from this participant, in total, 8.07% amount of trials were unusable due to failure in three second countdown or failure to record (13.33% of trials, including the excluded participant). It was also noted that in 8.77% of the total

trials, some participants used two hands to press multiple buttons at one time. When this occurred, both lights were coded in sync, so that both had the same timestamp.

3.5.2.1 Behavioural results

Search time

Participants were numerically quicker to find the target when it was on the cued side of space (M = 7.06s, SD = 2.74) in comparison to the uncued side (M = 8.25s, SD = 3.45). However, a paired samples t-test demonstrated that this difference was not significant ($t(19) = 1.50$, $p = 0.152$. $d_z = 0.35$).

First visits

The cued side was visited firstly just over 50% of the time (M = 51.93%, SD = 32.74). A one sample t-test, however, suggested that this was not significantly above chance level ($t(18) = 0.26$, $p = 0.800$, $d = 0.06$).

Density

On average, 58.35% (SD = 12.02) of visits were made to the cued side of space. This percentage was significantly different to chance level ($t(18) = 3.03$, p = 0.007, d = 0.69), suggesting that overall inspections were biased towards the high-probability side.

Number of visits

Approximately the same number of visits were made on cued ($M = 3.50$, $SD = 0.15$) and uncued trials ($M = 3.48$, $SD = 1.19$). A paired samples *t*-test showed that there was no difference between these visit rates ($t(18) = 0.06$, $p = 0.951$, $d_z = 0.02$).

3.5.2.2 Individual differences

Post-Experiment Questions

Post-Experiment Questions were scored in the same way as previous. Confidence ratings were compared using independent *t*-tests, to examine whether there was a difference in conscious awareness of the cue between those who rated the questions with high and low confidence.

47% of participants reported using a strategy to find the target (*binomial*, $p > 1.00$); unlike other experiments reported so far, this result was not significantly above chance level. Of those participants who did report a strategy, none of them (0%) provided explanations that demonstrated knowledge of target's probable location or using the sides of space to guide their strategies (*binomial*, $p < 0.001$). On average, confidence ratings were 4.75 ($SD = 1.19$). As no participants reported an awareness of the cue, a *t*-test could not be conducted on the confidence ratings.

For Question 2, 37% of participants reported having a sense of the target's likely location. This did not reach above chance level (*binomial*, $p = 0.359$). For these

participants, 26% demonstrated explicit knowledge of the target's location or the sides of space (*binomial*, $p = 0.064$). Mean confidence ratings for this question for the participants who consciously reported a sense were 4.80 (SD = 1.92). For the participants who reported not having a sense, the confidence ratings were, on average, slightly higher (M = 5.29, SD = 0.91). Confidence ratings did not significantly differ ($t(17) = -0.76$, $p = 0.458$, $d = 0.33$).

Finally, 42% of participants accurately identified the target's location when presented with a forced-choice option. This did not significantly differ to chance level (*binomial*, $p = 0.648$), suggesting that with a forced-choice question, most participants were unable to correctly guess the cued side. Confidence ratings between those who accurately guessed the target's probable location (M = 4.00, SD = 1.77) and those who did not (M = 4.73, SD = 1.85) did also not significantly differ ($t(17) = -0.86$, $p = 0.401$, $d = 0.40$). The results are summarised in **Table 3.11**.

Table 3.11 Experiment 3 - Post-Experiment Questions. Explicit and implicit knowledge was absent. $^{**}p < 0.001$.

Question	Answer	Result
1A - Strategy *"Did you use a strategy to search for the target in the environment"*	Yes: 47% (n = 9)	$p > 1.00$, less than 50% chance level.
	No: 53% (n = 10)	
1B - Strategy *"If YES please explain your strategy"*	Awareness: 0% (n = 0)	***p* < 0.001**,** less than 50% chance level.
	No awareness: 100% (n = 19)	
2A - Sense *"Did you have a sense of where the target was most likely to be in the environment?"*	Yes: 37% (n = 7)	$p = 0.359$, less than 50% chance level.
	No: 63% (n = 12)	
2B – Sense *"If YES please explain your 'sense' of the target's location"*	Awareness: 26% (n = 5)	$p = 0.064$, less than 50% chance level.
	No awareness: 74% (n = 14)	
3 - Final probe *"If I told you that the target was more likely to appear on one side, would you be able to guess which one?"*	Correct judgement: 42% (n = 8)	$p = 0.648$, less than 50% chance level.
	Incorrect judgement: 58% (n = 11)	

Questionnaire data

Cueing effect measures were calculated for all variables, using the same method as Experiment 2. **Table 3.12** demonstrates the results from the correlational analysis. Some, but not all, cueing effects were related to each other. As found in previous experiments, density cueing effect was positively correlated with first visits (r= 0.60, p = 0.006) and the number of visits (r= 0.79, p < 0.001). Search time cueing effect was negatively related to density (r= -.88, p < 0.001) and the number of visits cueing effects (r= -.71, p = 0.001). These relationships demonstrate that as the search time cueing effect value increased in positivity (i.e. more learning) the number of

visits cueing effect became more negative, as well as the density of visits to the cued side (i.e. less learning). There was no significant relationship between search time and first visit cueing effects (r= -.35, p = 0.140) or first visits and the number of visits cueing effects (r= .23, p = 0.352). No correlations between the EHI, SBSODS, confidence ratings from the Post-Experiment Questions, gender or any of the cueing effects reached statistical significance ($p > 0.05$).

Table 3.12 Experiment 3 - Pearson's Product-Moment Correlations (r and α) and a Point-Biserial Correlation (r_{pb} and α) for the cueing effect and questionnaire measures, $*p < 0.05$, $**p \leq 0.001$.

		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. Search cueing effect		-									
2. First visits cueing effect	*r*	-.35	-								
	α	0.140									
3. Density cueing effect	*r*	**-.88****	**.60***	-							
	α	**< 0.001**	**0.006**								
4. Number of visits cueing effect	*r*	**-.71****	.23	**.79****	-						
	α	**0.001**	0.352	**< 0.001**							
5. EHI	*r*	-.07	.16	.09	.02	-					
	α	0.772	0.518	0.716	0.942						
6. SBSODS	*r*	-.16	.28	.26	.15	-.30	-				
	α	0.524	0.239	0.286	0.547	0.207					
7. Question 1 – confidence rating	*r*	.07	-.08	-.21	-.14	-.30	< 1	-			
	α	0.766	0.756	0.386	0.574	0.211	0.996				
8. Question 2 – confidence rating	*r*	-.01	.25	-.03	-.23	-.36	.14	.38	-		
	α	0.964	0.296	0.895	0.347	0.134	0.560	0.114			
9. Question 3 – confidence rating	*r*	-.11	.11	.15	.03	-.01	-.15	.18	-.21	-	
	α	0.668	0.661	0.546	.899	0.974	0.538	0.453	0.389		
10. Gender	r_{pb}	-.27	.12	.26	.30	.18	-.24	-.35	-.10	.03	-
	α	0.260	0.613	0.275	0.221	0.456	0.330	0.144	0.681	0.890	

3.5.3 Discussion

Previous research has shown that probability cueing effects can be observed in large-scale search tasks, although they differ from behaviours recorded in visual search tasks in a non-trivial way. Smith et al. (2010) found that allocentric and egocentric coordinates needed to be aligned to effectively learn the probability cue in this type of environment. They also found that many participants reported knowledge of the target's whereabouts. Although the task used in Experiment 3 was like the task used by Smith et al. (2010), probability cueing was not reliably observed. Search time was no quicker if the target was cued or uncued, and the number of visits did not change depending on the target's location. First visits were also no more likely to be directed towards the cued side of space. Density was the only measure to show an effect, with the overall percentage of visits more likely to be directed towards the cued side. Post-Experiment Questions also demonstrated minimal learning, with many participants unable to identify the cued side of space even when given a forced-choice option.

It was unexpected that a probability cueing effect would not be demonstrated here when it had been previously demonstrated in a similar environment (see Experiment 2 in Smith et al. (2010)), under the same basic experimental parameters. However, the environment designed in this experiment was rectangular and, as a result, narrower than the Smith et al. environment. Participants did not need to travel far to find the target and could easily reach each light without expelling too much physical effort or energy. In comparison, the space used by Smith and colleagues was

larger, requiring greater movement. The closeness of the search items may have hindered the separation of the left and right sides of space. Smith et al. excluded all lights that were on the midline or within reaching distance of the participants start position. Although the midline was avoided in this experiment, it is possible that the relative narrowness of the space made it less likely that participants would perceptually segregate the left and right sides. Therefore, the smaller and narrower size of search space may have had a negative impact on probability cueing.

The reduced amount of movement needed to find the target may have also had a detrimental effect on the coding of the space in this context. As Jiang and Won (2015) explain, minimal viewpoint changes can influence probability cueing. In one of their experiments, the probability cueing task was adapted to a target present-absent task and was presented on a flat screen monitor, laid on a tabletop. In the middle of the screen was an occluding, opaque tower meaning that throughout each trial, participants had to move around the monitor to identify whether a target was present. Although not necessarily arduous, locomotion was present but kept to a minimum; arguably like Experiment 3, in which participants could easily reach several lights in one go by travelling little distance. Their results suggested that participants were unable to prioritise their attention to cued targets, but were when the opaque tower was lifted, removing the prioritisation of allocentric reference frames.

Although in this current experiment both egocentric and allocentric reference frames remained consistent, by stabilising the search array and start position, there may be a threshold in which locomotion, and therefore the spatial scale, has a detrimental effect on probability cueing. A large environment – such as the one used

by Smith et al. (2010) – requiring a great deal of physical effort and relative travel distance may be beneficial, and necessary, for effective probability cueing. On the other hand, this theory is in juxtaposition to Experiment 1A results. Although relatively large in visual nature, a VE is still reduced to the spatial scale defined by the representational space, meaning travelling distance is reduced, just as in Experiment 3. Physical effort is also absent, again, similar to Experiment 3. Furthermore, probability cueing can be observed when locomotion is completely removed and spatial scale is reduced to the size of a monitor, such as in visual search (Geng & Berhmann, 2002). It may be that there are even more factors at play in large-scale, realistic environments and that simply holding egocentric and allocentric reference frames constant will not always produce successful probability cueing under specific contexts.

It has been demonstrated previously that first head movements are biased towards the cued side of space during visually guided search (Won et al., 2015). One of the aims of this experiment was to take this research a step further and examine the eye movements of participants during a three second countdown at the beginning of each trial, before they explored the search space. These eye movements may have demonstrated indications of pre-planning a route or being biased towards the cued of space as the trial sequence progressed. Unfortunately, this data was not able to be retrieved, and every participant had an issue with eye tracking recordings. It is likely that measures of first visits recorded in this Experiment were indicative of first head movement direction; first visits showed no effect of probability learning, leading to

the conclusion that first head movements were not more likely to be towards cued target locations. However, future experiments should confirm this.

Participants were also probed about the probability cue after the experiment. There was a lack of awareness of the target's likely location, even in Question 3 when a forced-choice probe was presented. There is a stark contrast between the Experiment 1A and 3; 42% of participants identified the cued side correctly in the present experiment, whilst in Experiment 1A, 95% of participants correctly identified this. Equivalently, Smith et al. (2010) found a minimal number of participants could identify the cued side when, behaviourally, probability cueing was absent. For example, in Experiment 1, they report that 39% of participants could accurately identify the cued side – a percentage that is below chance level. Furthermore, there was no difference on any of the questions between the participants who rated their answers with high and low confidence; neither did confidence ratings relate to any cueing effects. Overall the Post-Experiment Questions reflect similar results to the behaviour results; participants were unable to bias their search towards the cued side of space and showed no understanding of the probability cue.

3.6 General discussion

Some researchers have suggested that visual search is a good model for real-world foraging behaviour (Klein & MacInnes, 1999; Thomas et al., 2006; Wolfe, 1994). It has been demonstrated that humans can bias their search to locations where targets appear more frequently in a search array (Geng & Berhmann, 2002). This probability cueing effect is well-established in visual search (e.g. Geng & Berhmann,

2002; Geng & Berhmann 2005; Jiang & Swallow, 2013). However, recently, probability cueing has been demonstrated in larger-scale, 3D environments (Smith et al., 2010; Jiang et al., 2014; Won et al., 2015) suggesting that this type of search behaviour may in fact be modelled in much more simpler tasks (i.e. it is domain-general). However, the mechanisms that probability cueing operates seem to differ across the two environments. Implicit learning of the cue has been found in visual search tasks, with participants reporting minimal knowledge of the target's likely location (Geng & Berhmann, 2002), in comparison to real-world search which has demonstrated explicit learning (Smith et al., 2010). Furthermore, larger-scale search tends to be far more complicated to achieve, with factors such as reference frames, physical effort, travelling distance and movement all needing to be accounted for (Smith et al., 2010; Jiang et al., 2014).

One approach to understanding whether visual search and large-scale search are domain-general or domain-specific is to examine probability cueing under a context that is a medium between the two. In this chapter, probability cueing was explored using virtual space; a spatial representation of a 3D environment, explored from an egocentric perspective, with the removal of vestibular cues and physical effort associated with locomotion. A VE was designed in which, using the keyboard, participants had to find a hidden target. Unbeknownst to them, the target was more likely to appear (80%) on one side of the search array, in comparison to the other (20%). Search time, first visits, density and the number of visits were recorded for each experiment.

Probability cueing was established for the first time in a VE in Experiment 1A. Participants effectively biased their search towards the cued side. Furthermore, participants reported minimal knowledge of the spatial statistics, with the target's location only being recognised upon the presentation of a forced-choice question. These results seem parallel to visual search studies, suggesting that learning may be below conscious awareness (Geng & Berhmann, 2002) and in contrast to the large-scale real-world search experiments in which learning has been found to operate consciously (Smith et al., 2010). This may be the case as searching through virtual space does not require the same amount of physical effort or expenditure as searching through a large-scale environment. Although button presses incur effort and energy expenditure, just as eye movements do, this effort is relative to that used in large-scale real-world search. It may be that the addition of physical effort, requiring live spatial updating, full-body movements and consistent vestibular information, may encourage conscious awareness of the cue.

A potential way of examining whether physical effort is necessary for conscious awareness is to evaluate probability cueing within VEs that require full-body movement to complete the task. For example, HMDs or treadmills could be used to create the illusion of real-world wayfinding and travel. There have been a series of experiments that have evaluated the cognitive effects of travel technique in virtual spaces (e.g. Ruddle & Lessels, 2009; Usoh et al., 1999). For example, Ruddle and Lessels (2009) investigated whether search differed dependent upon the amount of full-body translation and rotation available to the participant. Rotational movement involves turning around on an axis, whereas translational movements involves

moving from one position or viewpoint to another. They compared search performance (measured by re-inspection rate) on a task that required participants to find a target hidden within boxes. The VE was either controlled by: a HMD allowing real-world walking and physical movement (full translation and rotation), a tethered HMD controlled by gaze-directed travel (rotation only) or a desktop display controlled by gaze-directed travel (neither rotation or translation present). They found that participants who controlled the environment by their own movement, had superior search performance (on average, 10% re-inspection rate) in comparison to the other two groups were movement was restricted or absent (on average, 50% re-inspection rate). This is just one example of many other experiments that have shown the benefits of allowing full-body movements for exploration in VEs (e.g. Ruddle & Lessels, 2006; Ruddle & Lessels, 2009; Ruddle, Volkova, & Bülthoff, 2011). Thus, in the case of probability cueing, it may be that allowing physical movement and effort may encourage learning of the cue. It has also been shown that physical walking can increase reports of presence (Usoh et al., 1999), and as predicted before, stronger presence may encourage conscious knowledge of the cue. This should be investigated in future research.

Experiment 1B explored probability cueing in greater detail by dividing the trial sequence into smaller epochs. Only a handful of visual search studies have investigated this before, and they suggest that probability cueing occurs early in the trial sequence (Jiang & Swallow, 2013; Kabata & Matsumoto, 2012). The aim was to examine when learning occurred in virtual space. Unlike what was predicted based on the successful results of Experiment 1A, in Experiment 1B, probability cueing was

weak. There may have been differing results across Experiment 1A and 1B because of the difference in reward across the two experiments, in turn influencing motivation and engagement with the task. In Experiment 1A, participants were rewarded with money whereas in Experiment 1B, participants were rewarded with a course credit. The structure of the trials may have also made learning harder with regular uncued trials deterring search from the cued side of space, making search more even across the two sides of space.

Probability cueing was also attenuated in Experiment 2. In this experiment, the immersive qualities of the VE were enhanced by displaying the VE on a larger screen. It has been shown previously that more immersive systems incur greater reports of simulator sickness (Sharples et al., 2007) so in comparison to Experiment 1A, several changes were made to the environment to reduce this. The number of trials was reduced to 30 (rather than 60) to reduce exposure time in the environment. It has been shown that simulator sickness symptoms can occur with as little as 10 minutes exposure time, suggesting that more trials may have incurred higher sickness ratings (Jarger & Mourant, 2001; Wiederhold & Bouchard, 2014). The rotational speed was also halved, again, as previous research has shown that swift rotational movements can increase a sense of vection and sickness (Keshavarz, Hettinger, Vena, & Campos, 2014; Wiederhold & Bouchard, 2014). All textures were removed from the VE and instead solid colours were used, again to reduce simulator sickness (Jarger & Mourant, 2001). It can be debated, however, whether these changes instead had a substantial effect on learning.

It is surprising that probability cueing was weak in Experiment 2, in comparison to Experiment 1A. It is evident from search time that participants were slower at completing the task in Experiment 2 than they were in Experiment 1, with an average search time increase of approximately 10 seconds for both cued and uncued trials. This search time increase may have been due to the slowed rotational speed, introducing extra time to find the target. For example, more time may have been spent, rotating the controller viewpoint to then proceed with finding the target, in comparison to the rotational speed in the VEs used in Experiment 1.

Further to this point, the slowed rotational speed may have influenced the paths chosen during exploration. Participants may have chosen paths that incurred more straight lines, rather than rotations, although the increase in search time contrasts this. Alternatively, search paths may have consisted of several straight lines, with participants reversing rather than rotating. This backtracking behaviour has been shown in other VE experiments (e.g. Kaur, Maiden, & Sutcliffe, 1999; Moffat, Zonderman, & Resnick, 2001) and although some participants may consider this an effective strategy allowing 'over-learning' of an environment, it instead can incur great costs to navigation (Kirschen et al., 2000; Ruddle, 2001). Less effort would be required for this strategy, potentially adding an additional decrease in motivational state and task engagement. This could have influenced the rate at which the probability cue was learnt (Waller et al., 1998; Ruddle, 2001).

Supplementary to these points, the adjustments to rotational speed may have been why there were a handful of anecdotal reports concerning difficulties with the controls. This was not found in Experiment 1 in which the rotational speed was set to

a speed similar to normal walking pace. There have been reports of participants finding it difficult to control other VEs, which can be behaviourally demonstrated by impaired navigation and increased disorientation (Ruddle, 2001). Ultimately, for immersive virtual spaces to be utilised for training purposes, they must be navigated with ease, to enhance learning and increase behaviour transfer.

As well rotational speed, textures were removed from the floor and walls of the VE in Experiment 2 and instead were replaced by solid colours. With regards to previous research findings, it has been suggested that there is no difference in search behaviour and spatial learning between visually rich and sparse environments (e.g. Ruddle & Lessels, 2006; Tan et al., 2006). However, this definition of 'visually rich' varies from study to study. For example, in one of their experiments, Tan et al. (2006) used an environment that was similar to the one used in Experiment 1A; a visually sparse, fenced arena with a flag target hidden behind walls within it. This was compared to a more ecologically valid, visually rich environment consisting of additional cues such as distinct landmarks and rich textures within an underground cavern environment. In comparison, the visually rich environment used by Ruddle and Lessels (2006) was defined as 'photorealistic' with search cylinders presented to participants via a HMD within a scene designed to look like a laboratory space i.e. a desk with a computer on in the background. The cylinders were presented absent from any type of scene in the visually sparse environment.

A point to highlight here is that although the definitions of visually rich and visually sparse environments may differ between studies, all the environments discussed in the examples consisted of textured objects or arenas. In Experiment 2,

textures were removed and replaced by solid colours. In fact it has been shown that textures can benefit performance in VEs (Sinai et al., 1999). A study by Sinai et al. (1999) showed that egocentric distance estimation judgements were more accurate when brick textures were present, in comparison to grass and carpet. The authors argue that this is because brick texture has a high-density pattern, incurring symmetry and metric information. Similarly to solid colour, carpet and grass are low density. The removal of textures in Experiment 2 may have had a detrimental effect, making the probability cue harder to learn.

However, one should be cautious when concluding that *learning* may be affected by the removal of textures. This may imply that participants are learning to associate a specific texture with the target, rather than learning the spatial statistics of the array. Large-scale search studies have shown that a spatial component is necessary for probability cueing to be demonstrated (Smith et al., 2010); probability cueing is independent of saliency (Fecteau, Korjoukov, & Roelfsema, 2009; Stankevich & Geng, 2014). Smith et al. (2010) found that when uneven target distributions were associated with a colour rather than a hemispace, probability cueing was attenuated. Thus, it may be that removing textures effects navigational ability, in turn effecting the acquisition of spatial knowledge, rather than there being a direct relationship between texture removal and effective probability cueing. On the other hand, it may be that textures are more salient than colours, enhancing learning. Either way, the VE task used in Experiment 2 should be displayed using a desktop setup to see if results differ.

Participants were asked three questions once the experiment was finished, to probe any awareness of the cue. These questions are more comprehensive than those used in past literature (e.g. Geng & Berhmann, 2002; Jiang & Swallow, 2013) and aim to tap both explicit (Questions 1 and 2) and implicit (Question 3) awareness of the cue (Smith et al., 2010). Interestingly, across Experiment 1 and 2, even if the probability cue was not learnt, participants correctly guessed the cued side of space when given a forced-choice probe, suggesting that they may have had some partial awareness of the cue (Experiment 1A: 95% correct; Experiment 1B: 85%; Experiment 2: 100%). This contrasts with the results from the behavioural measures in Experiments 1B and 2 that showed attenuated probability cueing. The reason for this is unclear, but it may simply be that during the experiment participants have very minimal knowledge, but post-hoc this knowledge may have become reasonable, especially as the questions progress (Smith et al., 2010). On the other hand, it could demonstrate that although participants do not act upon it, they may have some knowledge of the cue. In the case of Experiment 1B and Experiment 2, with time, this knowledge may have been acted upon efficiently.

Finally, Experiment 3 examined probability cueing in a large-scale space. This experiment had two main aims: to replicate the findings of Experiment 2 by Smith et al. (2010) in an environment with similar parameters to their large-scale laboratory space and to evaluate eye movements in the time before a trial began to explore whether there were indications of pre-planning a route or biases in eye movements in cued locations. The environment was also designed to feature some of the same parameters as the VE, such as having the search items on the floor. Participants were

asked to search an array of LED lights, to find the target light that, as before, was manipulated to appear more on one side of space than the other. Unlike predictions and previous research, probability cueing in this context was weak.

As discussed previously, the lack of learning in Experiment 3 may be due to the design of the environment, meaning physical movement and effort was shunted. The perceptual distinction between left and right (or cued and uncued sides) may also have been difficult for the participants to visualise. In the Smith et al. (2010) research, there was a clear distinction between left and right sides of space, as the laboratory dimension were large and target locations along or near the midline point were excluded – in essence, the illegal locations formed an hour glass shape, so left and right was relatively obvious. As a comparison, it could be argued that the VE in Experiment 1 also included clear landmarks indicating the left and right sides of space; a brick pattern and a fence pattern on both respective sides. In this experiment, participants may have, unconsciously, used these two textures as an allocentric anchor that the cue could be assigned to (Smith et al., 2010), enhancing the distinction between left and right sides of space. The environment used in Experiment 3, on the other hand, was narrow and rectangular meaning the search items were close to each other. Visually, it may have been difficult for participants to differentiate the left and right sides of space, meaning the cued and uncued sides may not have been as perceptually clear. Under this context, the addition of a clear landmark may aid probability cueing (Smith et al., 2010; Smith, Wallace, Hood, & Gilchrist, 2009). Future experiments could address whether successful probability cueing in virtual and full-body search is dependent upon a perceptual distinction between left and right

sides. For example, textures and colours could be removed from the walls in the VE, or the dimensions could be narrowed to a rectangle.

In conclusion, probability cueing was only prevalent during a VE task when it was displayed on a desktop monitor and the uncued and cued trial order was randomised. In this instance, it operated below conscious level. Probability cueing was not demonstrated when the trial order was pseudo-randomised, nor was it demonstrated when the immersive qualities of the environment were enhanced. Finally, probability cueing was attenuated in a large-scale laboratory space environment.

Chapter 4 continues the comparison of probability cueing across environmental contexts. The chapter will primarily focus on the transfer of learning between virtual and real world spaces where full-body search is necessary. This is important when considering the impact that VEs have had on the modern industrial world. Training people to perform optimally in a VE and then expecting that learnt behaviour to be utilised effectively in the real world is now a common situation across many domains including military and medicine (Mazuryk & Gervautz, 1996). Examining the transfer of behaviour also give us insight into the learning and search mechanisms used in probability cueing, and may provide some answers as to whether this process is a domain-general or domain-specific in nature.

4 Transfer of probability cueing

4.1 Introduction

The study of behaviour transfer was revived with the advent of modern virtual reality systems (Moskaliuk, Bertram, & Cress, 2013). Behaviour transfer entails learning in one context and transferring the learnt behaviour to another. This can be undertaken between virtual worlds and the real world. Importantly, training in a VE offers many benefits to the user: it is safe, harmless, and risk free. For the trainer, it can be inexpensive (depending on what software or hardware is used) and less time-consuming and effortful than training someone on-the-go at a task in the real world. The trainer also has control over what items are presented and what events may occur within the environment, as well as having the possibility to monitor live performance of the users, to provide feedback (Rose et al., 2000). VEs are used in a variety of ways to train individuals to perform efficiently and safely in a situation modelled on the real-world, in the hope that once training reaches a peak, the individual can handle that situation proficiently in reality. For example popular training tools include: surgery simulators for medical staff, battlefield simulators for military personnel, and flight simulators for pilots (Mazuryk & Gervautz, 1996).

There are many questions surrounding the effectiveness of VEs as training tools. It is generally *assumed* that behaviour in one context transfers (Rose et al., 2000). However, the factors influencing effective transfer are infrequently examined, with many studies examining dependent variables within individual environments

rather than the changes in these variables *across* environments (e.g. see Tan et al. (2006) for a comparison of search time across desktop and immersive virtual worlds).

Testing behaviours in a simple VE (e.g. with minimal clutter) may offer insight into transferable behaviour. Gradually increasing the complexity and extracting the factors that influence transfer may also provide an understanding of the cognitive processes that are involved in the task. If behaviour transfer occurs across two different contexts, this may suggest that the two tasks comprise of the same mechanisms (domain-general), whereas if transfer does not occur then the underlying mechanisms may be different (domain-specific). Some researchers have suggested that the mechanisms that visual search exploits are the same mechanisms used in the real-world and VE space, arguing for domain-generality (Klein & MacInnes, 1999; Thomas et al., 2006; Wolfe, 1994). Thomas et al. (2006), for example, replicated inhibition of return in a VE and argued for domain-generality. However, there are a lack of studies examining the direct transfer and comparison between visual (2D), virtual (3D representation) and real (3D) space. If a behaviour learnt in visual space transfers to virtual space or even real space, this would suggest that it is domain-general. In contrast, if a learnt behaviour does not transfer to a different context, this may suggest it is domain-specific, in other words, it only exists or is optimal under specific contextual restraints.

Furthermore, whether behaviour can transfer across multiple contexts or mediums is also rarely studied. For example, it is not known whether progression from small-scale VE (e.g. a desktop monitor), to an immersive VE, followed by a short period of real world training, is necessary for behaviour to reach optimum

efficiency in an active real world testing phase. Research tends to instead focus on testing across multiple environments, individually, and concluding that the behaviour elicited in one is the same as the other (e.g. Klein & MacInnes, 1999; Thomas et al., 2006), rather than directly comparing the development and progression of learnt behaviour across environments (Rose et al., 2000; Waller et al., 1998).

One study that has examined VE transfer in a spatial context was by Waller et al. (1998). Participants were trained to navigate a maze under one condition, and were then transferred to a large-scale real-world, testing equivalent. In the training phase, participants either: explored a real-world maze freely for one minute, were given a map of the environment, received two minutes of exposure time in a virtual desktop environment, received two minutes of exposure time in a HMD VE or were given four minutes of exposure time in a HMD VE. In all conditions, participants were given guidance from the Experimenter on the first trial, indicating the most efficient route to take. In the testing phase, participants were required to "touch" checkpoints, in a specified order as defined in the training phase, as quickly as possible and without colliding with the walls. After six trials, participants were given two trials in which the layout of the training environment differed slightly to the testing maze. The aim of this was to encourage participants to use the representations of space they had developed in the training sessions, to determine how to overcome the obstacle.

Waller et al. (1998) found that, in general, across all conditions participants became more proficient as the experiment progressed. Transfer occurred across all conditions even when a small-scale, desktop VE was used. However, those who received four minutes of training in the HMD VE, surpassed those who trained using

a map, taking less time and producing fewer errors, after the second trial, suggesting that exposure time was important. Conversely, when the environment differed and participants relied on their mental representations, all groups performed worse. This suggests that environments or contexts need to be stable and consistent for accurate transfer to occur. This is difficult to achieve when, in practice, the real world is dynamic and can change rapidly.

So far, all the experiments in this Thesis have examined probability cueing. There has been one study that has examined the transfer of probability cueing across different tasks. Jiang et al. (2016) conducted a series of experiments that consisted of a training phase in which targets were unevenly located across space, and a testing phase in which distributions were even. Transfer of probability cueing was demonstrated by a continuous bias towards the cued side of space in the testing phase.

The authors found varying degrees of transfer. Probability cueing transferred between visual search tasks that differed in both stimuli type (letters vs. numbers) and difficulty (target and distractors were dissimilar/similar to each other) when counterbalanced across the two phases. However, probability cueing did not transfer when the saliency of stimuli differed between the two phases. When the target and distractor were the same colour (conjunction search), probability cueing was learnt, but not transferred to a task when the target and distractor were in different colours (simple feature search), and vice versa. They also found that probability cueing did not transfer between visual search and a visual foraging task. Arguably, the foraging task may have involved input from high order processes as decisions were needed to be made as to which chest to inspect, as participants were limited to one inspection

per trial. Another key point to note is that for all the tasks, including the foraging task, both the training and testing phases required eye movements and a button press to complete. To date, no researchers have tested whether probability cueing can transfer between two tasks, requiring different actions to complete.

Transfer studies can help provide insight into the mechanisms underlying behaviour. In the case of the studies by Jiang et al. (2016), probability cueing seems to be sensitive to task demands and qualities, suggesting that the distinction between domain-general and domain-specific mechanisms may not be so dichotomous. In the training phases, probability cueing was present and found under varying visual search contexts. However, when the training and testing tasks differed in their complexity, for example requiring pure visual guidance to higher-level decision-making, transfer was overridden. On the other hand, their findings demonstrate that probability cueing can transfer across generic visual search tasks that differ in slight changes of target/distractor similarities or physical appearance. Parallel to the study by Waller et al. (1998), this may suggest that a stable or highly similar environment across the training and testing phases is needed for accurate transfer.

One question surrounding the transfer of attentional biases across different contexts is *how* this is achieved. Bisley and Goldberg (2010) proposed a theory of attentional priority mapping. They claim that when an image is perceived, it is exposed to preattentive feature detection filters, creating a map for each feature. This map is built based on the strength of saliency across these features; the more important the feature is within the image, the more intense the weighting in the map. The feature maps are then combined and attention is allocated according to the

strongest weight within the map. The mapping is a 'winner-takes-all method', thus whatever features are deemed of low weighting are not attended too. The map updates on a moment-by-moment basis and can feature both bottom-up influences, such as perceptual saliency, and top-down influences, such as an individual's goal.

The spatial location of a target is particularly important and takes priority in the attentional weighting of a map. The allocation and direction of attention is primarily determined by where in the world the object of interest is located. A weighted map of these locations is created in the parietal cortex, which then guides the oculomotor system, to produce saccades and direct visual attention. Bisley and Goldberg (2010) use inhibition of return to evidence this. They suggest that new locations become priority within the map, whereas locations marked as 'already visited' become weighted less. Thus, attention and eye movements are directed away from them and the locations are not inspected. This is especially important when considering that new locations may induce high rewards, whereas locations visited previously may have deteriorations in their rewards. Combined with spatial memory and regular moment-by-moment updating of the map, the strong attentional priority mapping of new locations aids search efficiency.

The opposite applies in the case of probability cueing. After a period of training or several trials, the cued locations ("recently inspected") carry more perceptual weight and therefore attention is directed towards these areas first. Importantly, from previous studies, it is understood that probability cueing is persistent and can last for up to a week after training (Jiang, et al., 2012), whereas inhibition of return is relatively short-lived (~300ms; Nakayama & Mackeben, 1989).

This would imply that the attentional priority mapping designed during probability cueing tasks is resilient to interference, suggesting that transfer of this behaviour may be possible. What is questionable is whether this behaviour transfer occurs across the same task context or whether it can be different. It is not known whether the attentional priority map designed for the transfer of probability cueing is malleable or rigid.

Permitting that there is a degree of stability and similarity across the environments (Jiang et al., 2016; Waller et al., 1998) and that the attentional priority map is resilient to differing contexts (Bisley & Goldberg, 2010) transfer may occur between two tasks conducted in different contexts and that have different response outputs. Taking this evidence into account, the aim of Experiment 4 was to examine whether probability cueing could transfer between a VE and a full-body search task. In Experiment 3, probability cueing was attenuated in a laboratory task, hence transfer was only examined in one direction.

4.2 Experiment 4: Transfer of probability cueing

In the current experiment, two phases tested the transfer of probability cueing. Firstly, participants completed a 'training phase'. This phase was conducted in a VE - the visual aspects were the same as that described in Experiment 1A. To recapitulate, the target was hidden amongst other distractor items and presented on the floor of a virtual space. The aim of the task was for the participant to find the target as quickly as possible. Unbeknownst to them, the target appeared more frequently on one side of the search array than the other. The VE was displayed using a desktop monitor for

two reasons. Firstly, to reduce simulator sickness drop-out rate and, secondly, a published study (Waller et al., 1998) demonstrated that a desktop VE was sufficient for the learnt behaviour to be transferred to a real space.

After completing the training phase, participants completed a 'testing phase' in which the target appeared evenly across both sides of the array. This phase was conducted in a different environment: the laboratory as described in Experiment 3. In this environment, participants were presented with a series of LED lights on the floor and were required to find the target that was indicated by one of the lights illuminating upon being pressed. This task involved full body movements, and was presented in real space.

To allow a thorough comparison, search time, first visits, density and the number of visits were recorded from both environments. It was hypothesised that in the training phase: there would be a significant decrease in search time on cued trials, first visits and the overall percentage of visits (density) to the cued side would be above chance level and that the number of visits would be greater on cued trials. It was also predicted that a bias in search behaviour would be demonstrated towards the previously cued side of space in the testing phase. This would indicate transfer. For example, search time would be numerically faster to the previously cued side. However, probability cueing would need to be learnt in the VE for the behaviour to be transferred – if no learning occurred, no transfer would take place.

At the end of the experiment, participants were probed for their awareness of the probability cue. Half of the participants were asked about their experiences in the

virtual space first, whereas the other half were asked about their experiences in the laboratory space first. Parallel to the results from Experiment 1A, it was predicted that participants would correctly identify the cued side in the final probe. Considering that it was hypothesised that transfer would take place, it was predicted that when questioned about the laboratory space, participants would believe that the target appeared more frequently on one side of space also, even though in this environment it was evenly spread.

Additional questionnaire measures were also recorded, as per other experiments, including: strength of hand lateralisation, sense of direction, gender and the number of mean hours spent playing computerised games. Correlations were conducted to examine any relationships between these measures and the probability cue – however, in line with aforementioned experiments, it was predicted that relationships would not arise.

4.3 Method

4.3.1 Participants

20 participants were recruited from the University of Nottingham (eight females); originally 21 participants were recruited but one dropped out due to difficulty with the physical movement in the testing phase. Two participants showed signs of simulator sickness but both persisted with the experiment and chose not to withdraw. The age of the participants ranged from 19 to 30 years (M = 22.85; SD = 2.98). All participants had normal to corrected normal vision and, as recorded by the

EHI, all but one participant (EHI score: -100), were right handed (EHI score: M = 72.11; SD = 22.57). This was also confirmed with self-report. Nine participants reported English as their first language. All participants confirmed that they had not participated in any probability cueing experiments before. Participants were required to be physically mobile and were advised that on the day of the experiment they should wear non-restrictive clothing and tie all long hair back. Additionally, individuals who had previous experience with motion or simulator sickness were advised not to participate. Participants were paid £9 in exchange for their time.

4.3.2 Materials

Training phase: VE

The VE outlined in Experiment 1A (**Section 3.2.1.2**) was also used in this experiment. The only difference was the screen size; the VE was displayed on a standard 22-inch computer monitor (resolution of 1920 x 1080 pixels, 60Hz refresh rate), using a Stone desktop computer running Windows 7. Participants were seated centrally, 60cm away from the screen. To recapitulate, the environment was square in shape and consisted of adjoining textured walls (brick and fence textures) and a textured, 'grass' floor. 12 red hemispheres on the floor of the environment represented the search items; these items were positioned so that three items appeared within an invisible quadrant of the square environment. The positions of the search items were assigned according to the combination number (see **Section 2.1.3**). Participants were instructed to "walk over" each of the hemispheres in the environment, until the target was found. The start position was in the midpoint of the

adjoining walls and was either at the north or the south of the environment and was counterbalanced across participants.

Participants completed two blocks of 30 trials (60 in total), with the defining 'cued' (80%) and 'uncued' (20%) sides of space. Per block, in 24 trials the target was located on the cued side, and in six trials it was located on the uncued side. For the cued side, each location was sampled four times, and for the uncued side, each location was sampled once. For this experiment, trials were shown in a completely random order, so that target location repetitions were permitted. This meant that a target could appear in the same location successively, for example in trial one and trial two the target could be at location five. In previous experiments, these repetitions were omitted. It was decided to introduce this as participants may have previously learnt not to revisit certain locations (in particular, cued locations) increasing the chances of inhibition of return. In turn, this could potentially interfere with learning the cue. The target repeated on 7.08% of trials in the training phase (8.33% in Block 1; 5.83% in Block 2). As before, the cued and uncued side of space was egocentrically defined (i.e. the participants' left or right) and counterbalanced across participants.

Testing phase: Laboratory environment

The search environment used in the testing phase was the same as the environment used in Experiment 3 (**Section 3.5**). To recapitulate, the environment was rectangular (4m x 2m) in a laboratory space. One side of the rectangle was clearly marked (using coloured tape) and the start position was exactly half way

across this line (at 1m). All participants started from this position. The other three sides of the rectangle were surrounded by white walls. As with the VE, the environment was divided into four quadrants with three search items in each, totalling to 12 items. The search items were LED lights positioned on the floor. The positions of these search items were identical to the position of the search items in the VE space, hence the array did not change across environments.

Eye tracking glasses were not used in this study. This was because of the large amount of trials that were deemed unusable in Experiment 3. Instead, a 'webcam' integrated within a computer monitor (Apple iMac) was used to record the participants' movement. The computer monitor was positioned on the floor, behind the start position, and was tilted downwards so that the camera recorded the light presses and the participant's feet rather than their face. Each trial was recorded and saved as separate '.wmv' files using Windows Movie Maker. One Experimenter was needed for testing. The Experimenter started the recording just before the trial began and the participant entered the room, and then stopped it once the target was found. Full consent was given by the participants, all were aware of the camera at the time of testing and all acknowledged that video recordings would be used for data analysis.

In this environment, the target was represented by one of the lights that had batteries in; when the participant pressed this light, it illuminated, ending the trial. The target was located evenly, meaning it had a 50% chance of appearing on either the left or right side of space. Participants completed 24 trials in total, with each location sampled twice. As with the VE, the trials were randomised, allowing for

target location repetitions. The target's location was repeated across 4.17% of trials in the testing phase.

Similarities and differences across the environments

One of the aims of this experiment was to ensure that the environments were relatively like each other. Therefore, both environments contained the same amount of search items (12 in total), and these items were positioned in the same locations (i.e. the same search arrays). Participants always faced the same direction at the start of each trial. The search items in both environments were circular in shape and required some form of interaction to acknowledge that they had been visited. In the VE, this required 'walking over it' as directed and controlled by the participant interacting with the computer keyboard; in the laboratory environment, this involved physically moving and pressing the light. The environments differed slightly in their shape and colour; the VE was square and lined with textured walls whereas the vertical axis in the laboratory space was elongated and the environment was lined with white walls.

4.3.3 Procedure

After signing a Consent Form, participants completed the training phase in the VE. They were seated in front of the computer monitor and were asked to complete a practice trial. Participants were required to explore the environment and navigate over each search item using the arrow keys on the computer keyboard, until they found the target. A 'chime' sound provided the participant with feedback, meaning that the

"computer had registered" their visit to the search item[1]. Participants were told that if they did not hear this sound, they should "reposition and try moving over the item again" until the trial ended or the sound was heard. When the target had been located, the trial ended and a success message appeared on screen. 60 trials defined by cued and uncued target location probabilities, with a break after 30 trials, then proceeded.

Once the training phase was complete, the participant was then moved into the laboratory environment, which although was in the same building, was in a different room. It took the participant and Experimenter approximately five minutes to walk there from the training phase room. Participants completed one practice trial, followed by 24 trials with the target evenly spread across space. At the start of each trial, the participant was required to stand on the starting point and a three second countdown, timed using a stopwatch, was given. Upon the Experimenter saying "Go!", the participant was required to press, in any order they wished, the lights on the floor. The target was the light that illuminated upon being pressed. Once the target was found, the participant exited the room and was called back after the Experimenter had changed the location of the battery-powered light. Throughout the whole experiment, participants held a small ball in their non-dominant hand, to encourage the use of their dominant hand only and avoid pressing two buttons at once. Participants were offered

[1] In previous experiments, it was found that some participants struggled with the controls in the VE and made erroneous revisits to search locations. Previous research has demonstrated that the addition of audio can aid memory for objects in VEs (Dinh et al., 1999). Audio feedback was added and tested in a pilot experiment (n = 3; originally n = 4 were recruited but one participant dropped out due to simulator sickness). The data from this pilot experiment suggested erroneous revisits were less frequent across trials and that there was a proportional difference between search time on cued (M = 24.42s, SD = 15.67) and uncued trials (M = 25.63s, SD = 10.73). Therefore, for Experiment 4 (and Experiment 6, detailed later in Chapter 5) audio feedback was added.

a break half way through the trials, and were also told that they could have a break at any time throughout the experiment.

After the trials were complete, the participant was asked about gaming hours and completed the SBSODS and the EHI. Participants were given an adapted version of the Post-Experiment Questions that asked them about their experience in the VE and the laboratory space. The participant was instructed to read each question individually, answer each at their own pace and to not go back and change any of answers. The order of the questions was counterbalanced so that half of the participants were asked about their experience in the VE first (Questionnaire A) and vice versa (Questionnaire B). Each question was also followed by a confidence rating, from one (not confident at all) to seven (extremely confident). The questions were the same as previous experiments, firstly asking about the use of a strategy, followed by 'sense' of the target's location and a forced-choice probe. For the forced-choice question, participants were given a multiple-choice question that asked: "From where you started you searches, do you think: a) the target was more likely to be located on the left side of space; b) the target was more likely to be located on the right side of space c) the target was evenly located". Scoring of these questions was slightly different to that outlined in the previous experiments and is detailed in **Section 4.5.2**.

At the end of the experiment, participants were debriefed and were required to sign a Post-Experiment Checklist, confirming that they felt physically well after the experiment. The experiment lasted approximately 1 hour and 15 minutes.

4.4 Results

Training phase

As in other VE studies, each dependent variable was obtained using a series of software including: MazeAnalyzer, LabVIEW and Microsoft Excel. Data was not pre-processed for erroneous revisits as audio feedback was introduced to aid search.

Testing phase

Each trial was manually coded using 'VideoPad Video Editor Free' software (MacBook Air). Each video was watched carefully and coded, as in Experiment 3. All coded responses were recorded in Microsoft Excel. The Experimenter opened each trial individually and paused the video each time a significant event occurred. This event was either coded as: three second countdown begin; three second countdown ended; a light press. This event was recorded and so was the corresponding timestamp. Light presses were coded per the participants' perspective and were labelled from 1-12, using the same labels as the search items in the VE. For search time, the timestamp at the three second countdown end was subtracted from the timestamp of each light press, to get an accurate time for trial end.

All participants were instructed to use their dominant hand only to press the lights. One participant used their non-dominant hand for one trial but swapped back for the next trials. One participant also made one double light press. One trial, out of 480 trials across all participants, did not record properly. Therefore, for one

participant, only 23 trials were analysed rather than 24. Overall, and in comparison, to Experiment 3, this was the only missing data.

Analysis

In line with analysis conducted by Jiang et al. (2016), data from the training phase was firstly analysed, followed by data from the testing phase. Analysis for each environment (using ANOVA's and *t*-test's) was separated[2]. If learning in the training phase had transferred to the testing phase, then a bias in search behaviour should be demonstrated towards the *previously cued* side of space. For the testing phase, spatial learning was calculated according to whether the location or side of space was previously cued or uncued in the training phase, relative to the start position of the participant. For example, the number of visits for trial one in the laboratory space was coded and calculated based on whether the target was positioned in a previously cued or uncued location according to the VE. Furthermore, search time, density, first visits and the number of visits for the first 10 trials[3] in the testing phase was also derived, to examine any initial biases in search performance to the previously cued side of space.

[2] Although not reported here, and parallel to previous experiments, whether the cued side was on the left or the right, had no effect on probability cueing as demonstrated via all spatial learning measures.

[3] It is worth noting that because the trials were not divided into smaller epochs of trials when they were designed (as they were in Experiment 1B), the first 10 trials may contain different amounts of previously cued and previously uncued trials per participant, per measure. This caveat is discussed further in **Section 4.5**.

4.4.1 Behavioural results

Search time: Training phase

A repeated measures ANOVA with the factors *block* (two levels: Block 1; Block 2) and *trial type* (two levels: cued trials; uncued trials) was conducted. Median search time on uncued trials was numerically slower (M = 7.10s, SD = 5.61) than search time for cued trials (M = 15.57s, SD = 8.30). However, there was no significant main effect of trial type ($F < 1, f = 0.16$). There was, however, a main effect of block ($F(1, 19) = 5.76$, $p = 0.027$, $f = 0.55$), demonstrating faster overall search time in Block 2 (M = 15.47s, SD = 5.08) than in Block 1 (M = 17.19s, SD = 5.27). This main effect is demonstrated in **Figure 4.1,** along with the results from the testing phase. There was no significant interaction between the two factors ($F(1, 19) = 1.32$, $p = 0.265, f = 0.26$).

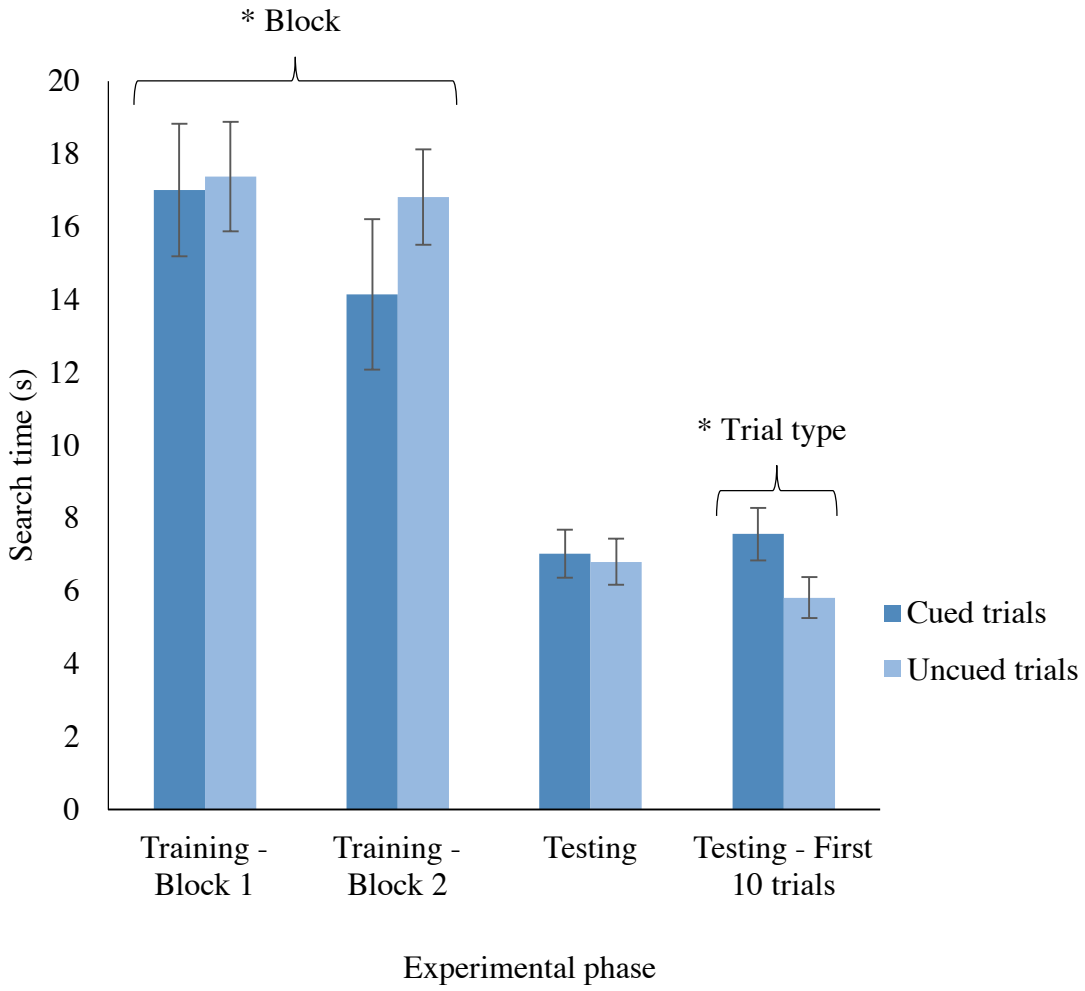


Figure 4.1 Block 2 search time was quicker than Block 1 in the training phase. Search time to previous uncued trials was quicker than previously cued trials in the first 10 trials. Data displayed for the testing phase are to previously cued and previously uncued trials. Error bars represent +/-1 standard error of the mean, *$p < 0.05$.

Search time: Testing phase

Median search times for targets on previously cued trials (M = 7.03s, SD = 2.94) and previously uncued trials (M = 6.80s, SD = 2.82) was compared in a paired sample t-test. This t-test was not significant ($t(19) = 0.31$, $p = 0.757$, $d_z = 0.07$) suggesting that search in this context was evenly spread.

Although this analysis was not significant, the first 10 trials of the testing phase were analysed to examine, in greater detail, any early transfer effects before the distribution may have become apparent to participants. Another paired samples *t*-test was conducted, with median search times for previously cued trials (M = 7.56s, SD = 3.23) and previously uncued trials (M = 5.80s, SD = 2.55) within the first 10 trials. This was significant ($t(20) = 2.28$, $p = 0.034$, $d_z = 0.78$). Search time in previously uncued trials was faster than search time in previously cued trials. This result is portrayed in **Figure 4.1**.

First visits: Training phase

The mean percentage of first visits to the cued side of space was 53.00% (SD = 39.72) for Block 1, with a numerical increase to 59.50% (SD = 42.75) in Block 2. Two one-sample *t*-tests showed that first visits in Block 1 ($t(19) = 0.34$, $p = 0.739$, d = 0.08) and Block 2 ($t(19) = 0.99$, $p = 0.333$, $d = 0.22$) did not significantly reach above 50% chance level, suggesting that first visits were not biased to the cued side of space in either blocks. However, the increase in first visits from Block 1 to Block 2 approached significance ($t(19) = -1.96$, $p = 0.064$, $d_z = 0.44$).

First visits: Testing phase

First visits to the previously cued side during the testing phase was 60.00% (SD = 31.52). A one-sample *t*-test showed this was not significantly above 50% chance level ($t(19) = 1.42$, $p = 0.172$, $d = 0.32$). When first visits were analysed for the first 10 trials, a similar result was achieved. 60.50% (SD = 30.34) of first visits

were directed towards the previously cued side, but this was not significantly above chance level ($t(19) = 1.55, p = 0.138, d = 0.35$).

Density: Training phase

Two one-sample *t*-tests were conducted to determine whether the overall percentage of visits made to the cued side were significantly more frequent than chance (50%). For Block 1 ($M = 60.73\%$, $SD = 19.38$), density was significant ($t(19) = 2.48$, $p = 0.023$, $d = 0.55$). Equivalently, for Block 2 ($M = 66.08\%$, $SD = 21.85$), density was significant ($t(19) = 3.29, p = 0.004, d = 0.74$). These results are illustrated in **Figure 4.2**, along with the results from the testing phase. A paired samples *t*-test also demonstrated a significant increase in the percentage of overall visits made to the cued side in Block 2 as compared to Block 1 ($t(19) = -2.52, p = 0.021, d_z = 0.90$).

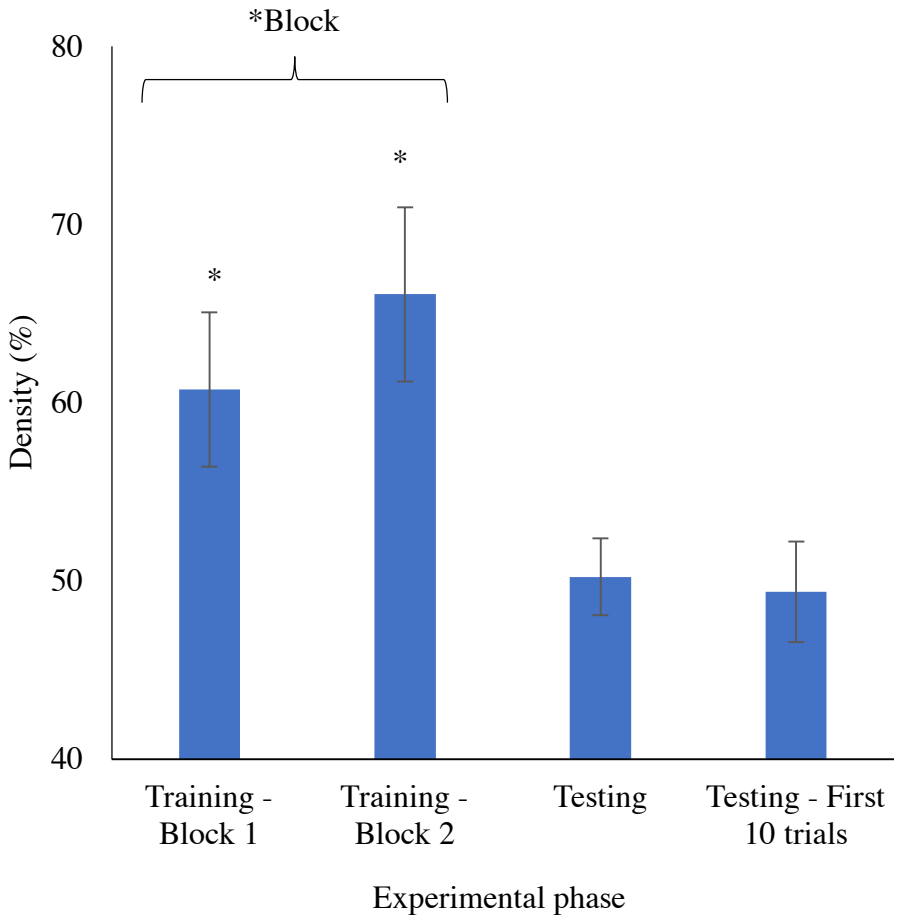


Figure 4.2 Density was significantly above 50% chance for the training blocks and significantly increased between them. Data displayed for the testing phase is to the previously cued side. Error bars represent +/-1 standard error of the mean, *$p < 0.05$.

Density: Testing phase

Density of visits to the cued side in the testing phase ($M = 50.23\%$, $SD = 9.60$) was not significant above chancel level ($t(19) = 0.108$, $p = 0.195$, $d = 0.02$). The first 10 trials also did not show significance above chance ($t(19) = -0.219$, $p = 0.829$, $d = 0.05$; $M = 49.38\%$, $SD = 12.67$).

Number of visits: Training phase

A repeated measures ANOVA with *block* and *trial type* as factors was conducted on the mean number of visits. For Block 1, there were slightly more visits made on uncued trials (M = 8.75, SD = 2.42) than cued trials (M = 7.39, SD = 2.28). This result was similar for Block 2 (uncued trials: M = 8.16, SD = 1.85; cued trials: M = 7.37, SD = 3.90). The ANOVA, however, revealed no significant main effect of block ($F < 1, f = 0.15$) or trial type ($F(1, 19) = 1.84, p = 0.190, f = 0.31$). There was also no significant interaction between these two factors ($F < 1, f = 0.17$).

Number of visits: Testing phase

A paired samples t-test showed no significant difference ($t(19) = 0.89$, $p = 0.383$, $d_z = 0.19$) between the mean number of visits made on previously cued trials (M = 3.55; SD = 0.18) and previously uncued trials (M = 3.47, SD = 0.37). This paired sample t-test was conducted again but instead with the mean number of visits from the first 10 trials, consisting of previously cued (M = 3.61, SD = 0.74) and uncued (M = 3.13, SD = 0.63) trials. This showed a significant difference ($t(19) = 2.17$, $p = 0.043$, $d_z = 0.82$). There were more visits when the target was situated in a previously cued location, in comparison to when it was previously uncued. This result, as well as the number of visits for all other experimental phases, is illustrated in **Figure 4.3**.

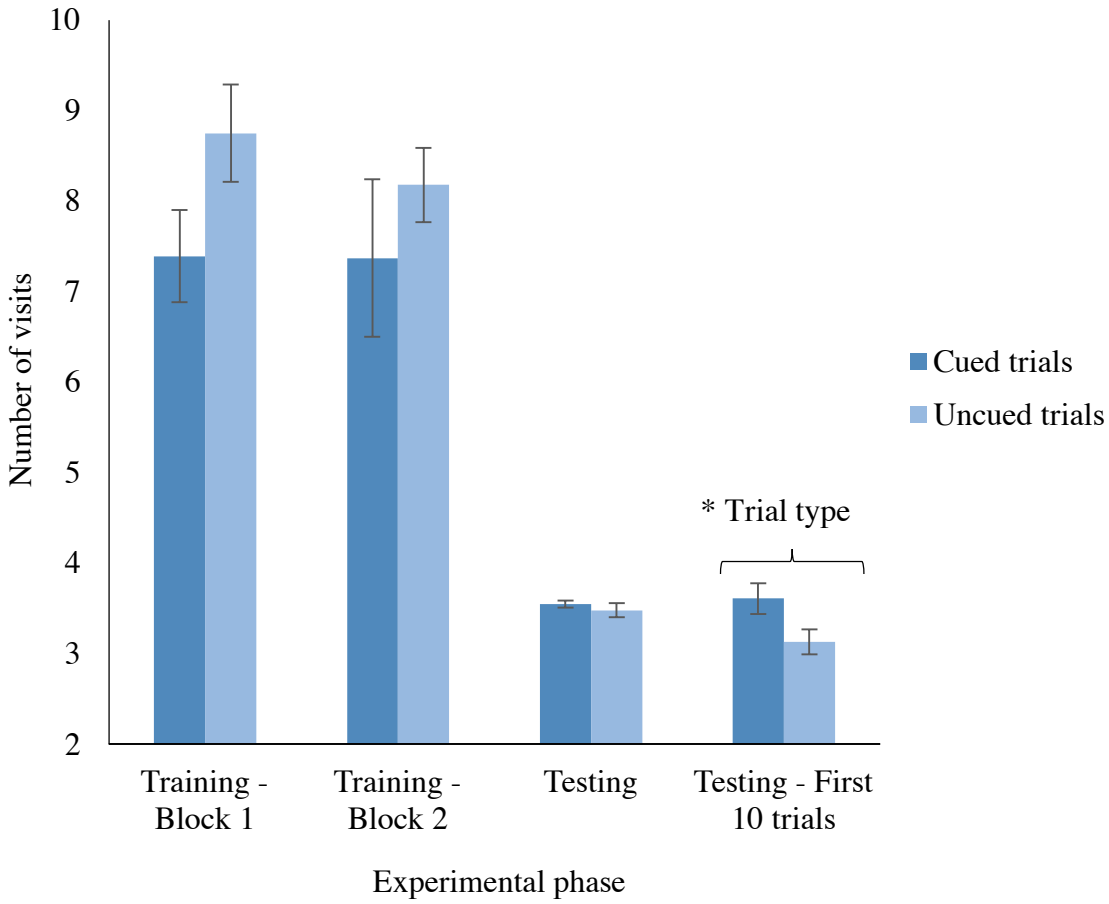


Figure 4.3 More visits were made on previously cued trials than cued trials in the first 10 trials. Data displayed for the testing phase are to previously cued and previously uncued trials. Error bars represent +/-1 standard error of the mean, *$p < 0.05$.

Interim summary

The behavioural results demonstrated a lack of significant results in both experimental phases. There was a general decrease in overall search time across the two blocks of trials in the training phase. Against predictions, within the first 10 trials of the testing block, search time decreased when the target was previously uncued in comparison to when it was previously cued. For first visits, there were no significant effects in the training and testing phases. On the other hand, for density, the overall

percentage of visits made to the cued side was significantly above chance in both blocks of trials in the training phase. Density in Block 1 and 2 also significantly differed, suggesting that visit rate to this side increased within the training phase. However, this behaviour did not transfer to the testing phase. Finally, there was no difference between the number of visits on cued and uncued trials in training phase, but within the first 10 trials of testing phase there were more visits made on previously defined cued trials than uncued trials.

4.4.2 Individual differences

Scoring the Post-Experiment Questions

The results from the Post-Experiment Questions were analysed using binomial tests per question, followed by independent *t*-tests on the confidence ratings. The order of the Post-Experiment Questions was counterbalanced across participants. Half received the questions concerning the VE first, followed by the laboratory space. This was known as Questionnaire A. The opposite (laboratory question, followed by VE question) was known as Questionnaire B. In total, participants answered: two questions concerning their strategies in either environment, two questions concerning whether they had a sense of the target's location and two forced-choice probes. For the questions referring to strategies or 'sense', a response containing reference to target likelihoods or sides of space (see **Table 3.1**) was scored as indicative of conscious awareness of the manipulation, no matter what the environment in question was. Thus, for example, if the target was more likely to appear on the right in the VE and the participant described that the target was more likely to appear on the right in

the laboratory space too, this was scored as indicating conscious awareness of the transfer of behaviour.

Finally, a correct judgement for the last questions did not indicate conscious awareness as it required a forced-choice prompt. These questions were scored in two ways. Firstly, they were scored correctly per environment. For example, reporting the target as even across space in the laboratory set-up would be correct, and alternatively reporting the target as more likely to appear on the right in the VE may also be correct. Secondly, the questions were re-scored to examine whether the answer selected for the laboratory space was correct for the cued side according to the VE. If so, this would indicate knowledge of behaviour transfer, at a below conscious level.

Post-Experiment Questions

All but one participant stated that they used a search strategy in the VE. This was significantly above chance level (95%; *binomial*, $p < 0.001$). With further probing, 30% of these participants provided some reference to the target's location. This was not significantly above chance level (*binomial*, $p = 0.115$) suggesting that many participants did not demonstrate conscious awareness of the cue in their explanations. Those who demonstrated no awareness of the cue, expressed mean confidence ratings of 5.86 ($SD = 0.66$), in comparison to 5.33 ($SD = 1.03$) for those who did not. An independent *t*-test showed that there was no significant difference between these ratings ($t(18) = -1.37$, $p = 0.187$, $d = 0.61$).

Similarly, for the laboratory space, all but two participants stated that they used a strategy to find the target (90%; *binomial*, $p < 0.001$). The two participants

(10%) that reported using a strategy also provided explanations that entailed transfer. Although a binomial was significant (*binomial*, $p < 0.001$), its direction was towards no expression of behaviour transfer. There was no significant difference in mean confidence ratings between explanations that were coded as expressing indications of transfer ($M = 6.00$, $SD < 0.01$) and those who expressed no conscious awareness of transfer ($M = 5.67$, $SD = 1.24$) ($t(18) = 0.37$, $p = 0.714$, $d < 0.001$). In total, any knowledge of the target's likely location in the VE and any conscious bias in search strategies in the laboratory space were absent.

In the second question participants were asked whether they had a sense of the target's location. For the VE, 25% of participants reported that they had a sense. Although this was significant (*binomial*, $p = 0.041$), it was in the direction of more participants reporting no sense of the target's location. When asked to explain their sense, 15% expressed knowledge of the cue (*binomial*, $p = 0.003$). Upon examining the mean confidence ratings, there was a significant difference in scores with those who expressed conscious knowledge ($M = 3.67$, $SD = 1.15$) scoring lower in confidence than those who did not express conscious knowledge ($M = 5.47$, $SD = 1.37$) ($t(18) = -2.13$, $p = 0.047$, $d = 1.42$).

Many participants (90%) said they did not have a 'sense' of the target's location when questioned about the laboratory space (*binomial*, $p < 0.001$). Furthermore, for the 10% of participants that did report a sense, when asked to explain this, only one of the participants gave an explanation that demonstrated behaviour transfer (5%; *binomial*, $p < 0.001$). Mean confidence ratings for those who did not express conscious knowledge of the target's likely location was 5.16 ($SD =$

1.77) and the participant who did express knowledge had a confidence rating of 3.00. Equal to the results from the 'strategy question', the results indicate that participants did not form a conscious understanding of the target's location in the VE and that this did not transfer to the laboratory set-up.

The final forced-choice question explicitly asked participants to identify where in the environment they thought the target was located. 50% of participants accurately identified the cued side of space in the VE. This was not above chance level (*binomial, p* > 1.00), and in line with behavioural results, suggested that overall there was a lack of learning in this environment. Mean confidence ratings did not differ between those who accurately identified the target's location ($M = 4.79$, $SD = 1.25$) and those who did not ($M = 4.30$, $SD = 1.42$) ($t(18) = 0.67$, $p = 0.512$, $d = 0.30$).

Responses regarding the laboratory environment were firstly scored according to whether the participant selected that the target was evenly distributed across the sides of space. 75% of participants selected that the target was likely to appear with an even frequency, which was above chance level (*binomial*, $p = 0.041$). Parallel to the VE, mean confidence ratings between the 75% of participants who correctly selected the target's even distribution ($M = 4.60$, $SD = 1.30$) and the 25% who did not ($M = 4.20$, $SD = 0.84$) did not significantly differ ($t(18) = 0.64$, $p = 0.530$, $d = 0.37$). When the responses were re-coded, 80% of participants did not select the previously cued side in the VE for the forced-choice probe (*binomial*, $p = 0.012$). Although this was above chance level, it was in the direction of more incorrect, than correct, judgements. Similarly to before, differences between average confidence ratings for those who selected the previously cued side ($M = 4.50$, $SD = 0.58$) and those who did

not (M = 4.50, SD = 1.32) did not significantly differ ($t(18) < 0.001$, $p > 1.00$, $d < 0.001$).

Interim summary

The results from the Post-Experiment Questions demonstrate that participants had minimal knowledge of the target's likely location in either environment. Most participants were unable to provide descriptions that indicated conscious awareness of learning during the training phase or conscious knowledge of transfer of this behaviour to the testing phase. Furthermore, these results were reflected when in the forced-choice probe, with 50% of participants able to select the correctly cued side for the target in the VE, and only 20% selecting that the target was cued to the same, correct side as per the VE, for the laboratory space. The results are summarised in **Table 4.1**.

Table 4.1 Experiment 4 –Post-Experiment Questions. Participants reported minimal knowledge of transfer, in line with behavioural results, *$p < 0.05$, **$p \leq 0.001$.

Question	Environment	Answer	Result
1A - Strategy *"Did you use a strategy to search for the target in the environment"*	VE	Yes: 95% ($n = 19$) No: 5% ($n = 1$)	***p* < 0.001****, in the direction of more participants reporting a strategy.
	Laboratory	Yes: 90% ($n = 18$) No: 10% ($n = 2$)	***p*< 0.001****, in the direction of more participants reporting a strategy.
1B – Strategy *"If you answer "YES", please give a brief explanation in the box below"*	VE	Awareness: 30% ($n = 6$) No awareness: 70% ($n = 14$)	$p = 0.115$, less than 50% chance level.
	Laboratory	Awareness: 10% ($n = 2$) No awareness: 90% ($n = 18$)	***p* < 0.001****, in the direction of no awareness of transfer.
2A – Sense *"Did you have a sense of where the target was most likely to be in the environment?"*	VE	Yes: 25% ($n = 5$) No: 75% ($n = 15$)	***p* = 0.041***, in the direction of no 'sense' of the targets location.
	Laboratory	Yes: 10% ($n = 2$) No: 90% ($n = 18$)	***p* < 0.001****, in the direction of no 'sense' of the targets location.
2B – Sense *"If you answer "YES", please give a brief explanation in the box below"*	VE	Awareness: 15% ($n = 3$) No awareness: 85% ($n = 17$)	***p* = 0.003***, in the direction of no 'sense' of the targets location.
	Laboratory	Awareness: 5% ($n = 1$) No awareness: 95% ($n = 19$)	***p* < 0.001****, in the direction of no awareness of transfer.
3A – Final probe *"From where you started your searches in the environment, do you think: i) the target was more likely to be located on the left side of space, ii) the target*	VE	Correct judgement: 50% ($n = 10$) Incorrect judgement: 50% ($n = 10$)	$p > 1.00$, less than 50% chance level.

was more likely to be located on the right side of space, iii) the target was evenly located across both sides of space.	Laboratory	<u>*Even distribution*</u> Correct judgement: 75% (n = 15) Incorrect judgement: 25% (n = 5)	***p* = 0.041***, in the direction of more participants correctly identifying the target's even distribution
	Laboratory	<u>*Transfer*</u> Correct judgement: 20% (n = 4) Incorrect judgement: 80% (n = 16)	***p* = 0.012***, in the direction of no transfer.

Questionnaire data

Cueing effect measures for all variables (search time, density, first visits and number of visits) were calculated as per previous experiments and entered in correlational analysis, along with the questionnaire data and confidence ratings from the Post-Experiment Questions. To recapitulate the calculations for the cueing effects, for search time and number of visits, the cueing effect was derived by calculating the difference between cued and uncued trials for each respective measure; this was calculated separately for each block and then a mean value between these two blocks was produced. Cueing scores for first visits and density were derived by taking the mean of Block 1 and 2. The more positive the individual value, the stronger the sensitivity to probability cueing. Cueing effects were calculated from the VE data as this part of the experiment is where learning should be prominent.

Results from the correlational analyses are in **Table 4.2**. As in the preceding experiments, there were highly significant relationships between the four cueing effects ($p < 0.05$). There was a significant, positive relationship between high confidence ratings for density cueing effects for Question 1 ($r = .45$, $p = 0.046$) and Question 2 ($r = .50$, $p = 0.026$). Thus, the more confident participants were with their search strategies and having a sense of the target's likely location, the more likely they were to direct their visits to the cued side of space. These positive relationships were also found between Question 2 confidence ratings and search time cueing effect ($r = .56$ $p = 0.011$) and the number of visits cueing effect ($r = .45$, $p = 0.046$). The positive relationship between confidence ratings for Question 2 and first visit cueing effect approached significance ($r = .43$, $p = 0.057$). Finally, the lower the confidence

scores for Question 1, the lower the average number of hours reported playing computerised games was (r= -.55, p = 0.011). All other results from these correlations did not reach significance ($p > 0.05$).

Table 4.2 Experiment 4 - Pearson's Product-Moment Correlations (r and α) and a Point-Biserial Correlation (r_{pb} and α) for the cueing effect and questionnaire measures, $^{*}p < 0.05$, $^{**}p \leq 0.001$.

		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
1. Search cueing effect		-										
2. First visits cueing effect	*r*	**.66****	-									
	α	**0.001**										
3. Density cueing effect	*r*	**.86****	**.85****	-								
	α	**< 0.001**	**< 0.001**									
4. Number of visits cueing effect	*r*	**.89****	**.63***	**.84****	-							
	α	**< 0.001**	**0.003**	**< 0.001**								
5. EHI	*r*	.04	-.07	.03	.04	-						
	α	0.864	0.766	0.912	0.866							
6. SBSODS	*r*	-.29	-.28	-.31	-.02	.19	-					
	α	0.223	0.236	0.178	0.938	0.417						
7. Gaming hours	*r*	-.03	-.04	-.10	-.21	.04	-.22	-				
	α	0.886	0.874	0.665	0.385	0.876	0.352					
8. Question 1 – confidence rating	*r*	.31	.21	**.45***	.30	.08	.05	**-.55***	-			
	α	0.185	0.377	**0.046**	0.196	0.751	0.835	**0.011**				
9. Question 2 – confidence rating	*r*	**.56***	.43	**.50***	**.45***	.28	-.17	-.07	.32	-		
	α	**0.011**	0.057	**0.026**	**0.046**	0.233	0.469	0.760	0.167			

10. Question 3 – confidence rating	*r*	-.11	-.24	-.14	-.03	-.11	.26	-.05	< 0.001	-.11	-	
	α	0.643	0.308	0.558	0.915	0.636	0.270	0.843	> 1.00	0.649		
11. Gender	r_{pb}	.10	.09	.13	-.06	.25	-.20	-.06	.18	-.11	-.08	-
	α	0.667	0.718	0.591	0.805	0.282	0.398	0.819	0.440	0.633	0.739	

4.5 Discussion

The current experiment examined whether probability cueing could be transferred from a VE (training phase) to a full-body search task (testing phase). Contrary to predictions and previous results, probability cueing was weak in the training phase. There was no bias in search behaviour towards the previously cued side of space, across any spatial learning measures, in the testing phase.

Density encapsulates the percentage of visits made to the cued side of space during the trial sequence. Density was above chance level for both training phase blocks, and these blocks differed from each other, insofar as density increased as the training progressed. This was the only measure that showed a significant effect in the training phase. However, density to the cued side did not transfer to the laboratory space; there was no bias towards the previously cued side of space in all 24 trials or within the first 10 trials.

To examine whether behaviour transfer occurred early in the testing phase, each measure was also derived from the first 10 trials. There were two significant effects in this analysis. The number of visits to the previously cued side was found to be greater than the previously uncued side in these 10 trials, yet there was no effect of trial type in the training phase or across 24 trials in the testing phase. Similarly, search time showed an effect in these trials, but there was no overall significant effect of search time in the training or across all trials in testing phase. Against predictions, this analysis demonstrated that search time was quicker when the target was previously uncued, in comparison to previously cued. It may be that participants naturally

favoured the previously uncued side during their initial searches in the testing phase. However, consistent with other experiments, the laterality of the previously cued side had no effect[4].

Although these results may seem striking, it is worth highlighting that the trials were not designed in separate epochs, unlike in Experiment 1B. This meant that some participants experienced more previously cued trials (n = 7) than previously uncued (n = 5) within the first 10 trials, and vice versa. It also meant that some participants experienced evenly sampled locations (i.e. five locations per side; n = 8). In total, across all participants, 49% (n = 98 trials) of trials within the first 10 were to previously cued locations and 51% (n = 102 trials) of trials were to previously uncued locations. Although these percentages are numerically close in value, this may have potentially drawn participants more towards the previously uncued side during the first 10 trials and accounted for this difference in search time across the two trial types, for example. The opposite may have occurred for the number of visits. Even so, this may have introduced bias in this analysis, conducted across all measures. A solution to this would be to control for the trial ordering using separate epochs (akin to Experiment 1B), ensuring that an event amount of previously cued and uncued trials occur per 10 trials.

There may be two methodological reasons why probability cueing was not learnt in the training phase. In comparison to the VE task used in Experiment 1A, the task differed in two ways. Firstly, audio was added, so that when a search item was visited, the participant received feedback regarding whether the computer had

[4] These findings are not reported in **Section 4.5**.

registered their visit. The aim of this was to reduce the erroneous revisits that were reported in previous VE experiments. Even though it was strongly emphasised to participants that they should pay attention to the audio feedback, they may have still made these revisits, by ignoring or misunderstanding the importance of the audio. Furthermore, it is difficult to establish from the data whether the revisits committed were erroneous or not, as upon replaying the trials, the sound was absent. Therefore, without certainty, the trials were not cut in any way, but it should be known that the data may include spurious visits.

The second difference between the current and previous VE tasks is that target location repetitions were allowed. For example, a target could appear at region five, three times, whereas in Experiment 1A, repetitions were limited so that the target's location could not repeat on successive trials. Although much literature suggests that repeating a target's location can aid probability cueing (e.g. Geng & Behrmann, 2005; Kabata & Matsumoto, 2012; Walthew & Gilchrist, 2006), this literature is limited to visual search. Currently, there are limited investigations into the influence of intertrial repetition priming in probability cueing tasks conducted in large-scale space or virtual worlds. In one analyses, Jiang et al. (2014) removed trials in which the successive trial was also defined as cued and found that probability cueing was still present in a large-scale search task that involved only eye movements to complete. However, this analysis is dissimilar to traditional intertrial repetition priming analyses. Rather than examining *specific target locations*, the authors removed repetitive trials that were defined as a cued, for example, if a target appeared in the top left and top right cued quadrants successively, these trials were removed. This was done so as target

repetition locations were limited in their task – there were 64 locations in which it could occur. In the current experiment, anecdotally, some participants commented when a repetition at *a specific location* occurred, especially in the laboratory space. Potentially, before acknowledging the target repetitions, some participants may have been avoiding locations that had occurred on the previous trial; performing inhibition of return. Either way, further investigations need to be conducted to understand how intertrial repetition priming and statistical learning may interact within differing environments.

As explained in **Section 4.1**, Waller et al. (1998) reported a significant transfer of behaviour between a VE and real-world environment. They conducted their experiment by alternating the training and testing phases between trials. For each trial, participants were trained and then exposed to the real-world maze; upon completing this, they would then be trained again and then tested for six successive iterations. Training and testing participants in this manner within the current experiment may have had differing effects on the transfer of probability cueing. It may be necessary that training needs to occur in conjunction with testing so that improvements in performance can be updated gradually. However, practically, this is not how training occurs in applied contexts; individuals are trained then exposed to the real-world situation in which the learnt behaviour should transfer too. Furthermore, it has been shown that probability cueing can transfer between visual search tasks (Jiang et al., 2016) which have the same ordering of training and testing phases, as conducted in the current experiment. Nonetheless, it may be of interest to examine whether training

and testing phases that occur in different environments need to be ordered in an alternating way to aid transfer.

A consideration of how probability cueing transfers raises the possibility that the environments, or tasks, used to present the paradigm, may need to share several qualities. For example, the visual search tasks used Jiang et al. (2016) rely primarily on eye movements to find the target and a button press to respond to its whereabouts. In the case of the current experiment, two tasks presented within differing contexts that required two separate actions to complete were used. Sharing similar qualities, such as modalities required to complete the task, between training and testing, may enhance transfer. This has been shown in an experiment by Larrue et al. (2014), who found that when participants had to reproduce a learnt path in a real-world testing environment, it was important to ensure that rotational and vestibular information in the training phase matched the information required during testing. When participants were trained in a real-world situation or in a VE with a treadmill that had rotation, they significantly outperformed those who were trained in a VE controlled by treadmill without rotation or a joystick. Although this experiment differs from the transfer results from Waller et al. (1998), it is important to note that in the conditions used by Larrue et al. (2014) and the current experiment, participants were specifically trained to perform a task rather than given exposure time and free movement within a similar environment during the training phase. Overall, it may be that training participants in a highly immersive VE, that is controlled with full-body movement for example, may encourage learning and therefore transfer to laboratory or real-world spaces.

Theoretically, being consistent across contexts and interactions within an environment utilising probability cueing, may have an impact on attentional priority mapping (Bisley & Goldberg, 2010). Consistency may stabilise attentional priority mapping and keep the weighting of the cued locations in precedence. Thus, accurate transfer may reflect inflexibility or slow updating of attentional priority mapping, rather than malleability, when behaviourally relevant spatial locations differ across two contexts. This has been evidenced in a study by Gollomb et al. (2008), who claim that attentional priority maps are organised in retinotopic coordinates. As we move our eyes within external space, spatial locations change, and permitting that the location is deemed behaviourally relevant, it will stay attended too but will form a new spatiotopic (world-centred/allocentric) coordinate. Thus, as a map is organised retinotopically (eye-centred/egocentric), it is updated quickly in response to each eye movement, creating new *retinotopic* coordinates based on the new *spatiotopic* coordinates of the attended location. Therefore, retinotopic coordinates are adaptable whereas spatiotopic coordinates are stable.

Experimentally, this was shown by Gollomb et al. (2008) by measuring eye movements during a task in which participants were explicitly instructed to attend spatiotopic locations. This resulted in delays in eyes movements, with gaze lingering at the previously relevant retinotopic location during the update to the new spatiotopic location. Thus, updating the map can take time. They also showed that attention *only* updates if the new spatiotopic location is of relevance to behaviour. This research may suggest two different outcomes for the transfer of probability cueing. Firstly, probability cueing may not transfer at all when the environment is so different that the

map cannot distinguish whether the new spatiotopic location is of relevance to gain attentional priority. Research has suggested that the previously learnt cued locations may still be tagged as behaviourally relevant even when the target distribution becomes even across space if the environment and stimuli are *identical* across testing and training phases. For example, using the same visual search tasks across both phases, Jiang et al. (2014) found that a bias in first saccadic eye movement prevailed during the testing phase.

However, in other experiments, Jiang et al. (2016) found that transfer across two different tasks (e.g. visual search and a foraging task) did not occur, potentially suggesting that the attentional priority map may be inflexible. This could instead demonstrate that the attentional priority map is so flexible and that the update occurs so quickly that the locations in the testing phase become tagged as irrelevant very early on because they genuinely are behaviourally irrelevant. However, if this were the case, it would be expected that first visits may show an initial bias to the cued side with a large dissipation as the trials progress. This was not the case in this experiment, but it may be worth examining even smaller epochs of trials in the future to establish this.

A third theory is that the transfer of probability cueing may simply occur at an extremely slow rate when a task that is dissimilar in nature is introduced. For example, this may occur when the two tasks require different action outputs or when the environmental search space is different in its dimensions (e.g. 2D vs. 3D). This theory has been evidenced, for example, Jiang et al. (2016) found that the transfer of probability cueing may be slower than expected. When probability cueing did transfer

across two visual search tasks that differed in their stimuli type (letters to numbers), reaction time was still biased towards the previously cued side, but it was slower overall. Patients who develop hemispatial neglect after parietal lobe damage also demonstrate an overall slowed learning of the cue (Geng & Behrmann, 2002; Shaqiri & Anderson, 2012). In line with the attentional priority mapping theory (Bisley & Goldberg, 2010), this may suggest that the parietal lobe is an important, and potential candidate brain region for learning and transfer of the probability cueing. This possibility is discussed more in the next chapter.

As well as behavioural measures, participants were asked a series of questions to probe their awareness of the probability cue and any knowledge of behaviour transfer at the end of the experiment. The answers to these questions were in line with the behavioural results. There was a lack of probability cueing in the VE and a lack of knowledge of the cue in any of the Post-Experiment Questions, including when a forced-choice probe was given. Because there was a lack of learning in the VE, there was also minimal behaviour transfer and knowledge of this when questioned about the laboratory space. Most participants believed that the target in this environment appeared with an even frequency across space, which was in fact true.

One recurring issue is that the questions are provided to participant's post-experiment. For the participants in this experiment particularly, this meant answering a set of questions on a task that was conducted a while before. This lengthened time could potentially impact the results as participants would have to be more reliant upon a relatively distant memory of the VE task. However, participants could not have been asked after the training phase as this may have impacted how they searched in the

testing phase. Future experiments could partly address this by examining the transfer of probability cueing from a laboratory space (testing phase) to a VE (training phase) with even target spatial likelihoods, to examine whether both behavioural and questionnaire results are like the current experiment.

Probing conscious awareness is hotly debated amongst the literature (see Tunney and Shanks (2003) for a useful commentary on this), and a general criticism of post-experiment questioning is that during the task, decisions may have been dissimilar to those described after the experiment (Smith et al., 2010). However, measuring awareness during the experiment is difficult to do without introducing experimenter bias or increasing participant curiosity during the experiment, leading them to potentially develop their own theories and purposefully change their search strategies to meet these expectations. Although confidence ratings do not rid this caveat, it has been suggested that the more confident participants are, the more likely they are to be correct in their response (Ais, Zylberberg, Barttfeld, & Sigman, 2016). This is reflective of the positive relationships that were found between the confidence ratings for Question 1 and Question 2 of the Post-Experiment Questions, and strong cueing effect measures. Stronger probability learning entailed higher confidence scores.

Overall, probability cueing did not reliably transfer between a VE and a full-body search task. Experiment 4 demonstrates that small methodological changes may have a large impact on successful probability cueing in the training phase, as probability cueing was not established during this phase. As this was the case, it is difficult to answer whether probability cueing *can* transfer across environments and

whether it is a domain-general or domain-specific mechanism. This experiment does, however, suggest the potential importance of keeping the environments or contexts as similar as possible between training and testing phases, and emphasises how attentional priority mapping may be difficult to update if similarities are absent or inconspicuous. The next chapter moves on from behaviour transfer and basic probability tasks, and instead reviews the potential neural region supporting probability cueing within: visual search, virtual search and full-body search.

5 The neural basis of probability cueing

5.1 Introduction

Although probability cueing has been established under varying visual search (e.g. Geng & Berhmann, 2002, Jiang & Swallow, 2013) and real-world constraints (e.g. Pellicano et al., 2011; Smith et al., 2010), the underlying neural mechanisms that play a role in efficiently biasing search are largely unknown. Candidate regions have been proposed by researchers, including the superior colliculus (Geng & Berhmann, 2002) and higher order brain regions such as the parietal lobe or hippocampus (Smith et al., 2010), but the precise neural correlates have not yet been systematically investigated.

One way to gain an insight into the neural mechanisms is to study whether probability cueing is disrupted in patients with attentional disorders. Currently, there have been two studies that have investigated this in hemispatial neglect patients. Hemispatial neglect is a demonstrated by a failure to detect information that is presented to the contralesional side of space (Husain & Rorden, 2003). Neglect can occur from lesions in either hemisphere, but the disorder tends to be common in patients that have lesions to their right parietal cortex (RPC) (Halligan et al., 2003).

Geng and Berhmann (2002) presented neglect patients with a probability cueing search task and found that although they were numerically slower at allocating their attention towards the cued side, compared to healthy age-matched controls.

Hemispatial neglect patients were just as able to learn the probability cue as controls, even when targets were presented on the contralesional side of space. This seems paradoxical, given the behavioural characteristics of neglect, and the authors therefore proposed that an intact attentional system may not be necessary for probability cueing. Instead, they proposed an 'attentional orienting system' that works at an oculomotor level. Firstly, an early sensory process involves a feedback system between the learnt expectancies of the target's location and the early visual areas. This feedback loop enhances the processing of targets located on the high-probability side of the search array. The early sensory process is coupled with a later oculomotor process, namely one that uses presaccadic activation within the superior colliculus, which is primed and modulated by the target's frequent location. Thus, the functional basis for probability cueing is dependent upon statistical learning of the search array and this is induced at an oculomotor level.

Shaqiri and Anderson (2012) also investigated probability cueing in age-matched control participants and patients with right hemisphere damage, with members of the latter scoring above and below the clinical cut-off for hemispatial neglect. They found that when the target repeated in or near cued area(s), hemispatial neglect patients showed no reaction time (RT) benefit. When statistical learning was examined, they found that patients *without* hemispatial neglect biased their search towards the left, but that their search was not specific to a 'hot spot' area where it appeared 75% of the time. Patients *with* hemispatial neglect showed the opposite effect, with a bias towards the hot-spot, but no bias when the target appeared in the

background (12.50% of the time) on the left. Thus, probability cueing via statistical learning was partially intact.

The assumption that probability cueing may work at an oculomotor level complies with the results from the work by Shaqiri and Anderson (2012), when considering the assumption that probability cueing may be due to statistical learning only. Although attenuated, hemispatial neglect patients demonstrated a statistical learning effect, suggesting that eye movements may be biased towards the locations of high probability targets, and that an intact RPC may not be necessary for learning of this type.

However, a pure oculomotor account does not provide justification for why hemispatial neglect patients showed no probability cueing to targets within the background on the left cued side or during repetition priming trials. Probability cueing in these patients operated at a 'narrowed' statistical learning level, with search biased towards targets when they were in the hot spot. Additional research has shown that location priming in hemispatial neglect patients is dependent upon conscious acknowledgement of targets (Kristjánsson, Vuilleumier, Malhotra, Husain, & Driver, 2005). For example, Kristjánsson et al. (2005) allowed patients an infinite amount of time to respond to a target; patients were slower to respond to targets that appeared on the contralesional side (i.e. the left) compared to the ipsilesional side of space. However, when display times were reduced to 200ms, in turn minimising exploratory saccades, intertrial repitition priming only occurred when a target on the left was detected on the preceding trial whereas an undetected target on left incurred no priming on the preceding trial. On the other hand, studies in healthy subjects have

suggested that positional priming and probability cueing can still occur with minimal display times (e.g. Walthew & Gilchrist, 2006), suggesting that within the intact brain, conscious detection of the target occurs quickly. This evidence does not discredit the involvement of saccades during search, but instead an oculomotor account of probability cueing may be too simplistic. Conscious detection of a target seems to have an impact on learning, indicating that higher order brain regions, such as the RPC, may be involved in probability cueing.

There is a copious amount of evidence to suggest that the right parietal lobe plays an important role in attention (for reviews see: Colby & Goldberg, 1999; Sack, 2009). However, on a general level, there are two theories that implicate the right hemisphere in attention allocation. These are explained in detail in **Section 1.1.4**, but will be briefly revisited. The theory of Hemispheric Rivalry (Kinsbourne, 1987) suggests that in the intact brain, reciprocal inhibitory activity determines the direction of attention. In patients with hemispatial neglect, this process is disrupted, with the intact hemisphere exerting increased over-activity and greater attentional control ipsilateral to this hemisphere. Heilman and colleagues (1979; 1980) instead suggested that the right hemisphere is dominant in directing attention, across both hemifields, compared to the left hemisphere which purely controls the right side of space. These theories are based on hemispatial neglect symptoms that support the idea that right hemisphere damage incurs greater loss of attentional direction function (Husain & Rorden, 2003).

Recent theories, and evidence, have taken a more specific approach and have proposed that the parietal cortex plays a role in directing attention. Bisley and

Goldberg (2010) suggest that the lateral intraparietal cortex (LIP) may be involved in priority mapping and the perceptual weighting of stimuli. Greater activity in this region would be induced by objects in the world with high behavioural priority (and therefore high attentional weighting) compared to objects with low behavioural priority. The mapping is a 'winner-takes-all method', thus whatever features are deemed of low weighting are not attended too. They suggest that the attentional map is 'created' within the LIP, which is then 'read' by the oculomotor systems to guide attention and direct eye movements towards the behaviourally relevant location.

Corbetta and Shulman (2002) also implicate the LIP as a core functional component in building attentional priority maps and guiding attention to behaviourally relevant locations. They describe how the attentional deficits observed in hemispatial neglect patients are primarily right hemisphere lateralised. They claim that an intricate ventral frontoparietal network directs attention to behaviourally relevant sensory stimuli. The intraparietal sulcus (IPS) provides the temporoparietal junction with information regarding the stimuli's relevance, whilst the frontal regions evaluate the novel stimuli.

Some cognitive neuroscience techniques have been used to evidence these theories in neurologically intact populations. Of most relevance to this Thesis, transcranial direct current stimulation (tDCS) has been used to demonstrate that modulating the RPC can induce biases in target detection and search behaviour. tDCS involves emitting a weak anodal or cathodal current, non-invasively to brain region(s) of interest. Studies have examined the effect of RPC stimulation on spatial attention (e.g. Benwell et al., 2015; Giglia et al., 2011) and search behaviour (Ball et al., 2013;

Clark et al., 2012; Ellison et al., 2014), and are also summarised in **Section 1.2.2.2**. For example, Ball et al. (2013) demonstrated that cathodal tDCS to the RPC (hereafter, CRPC) slowed RT, compared to sham, during the first two blocks of trials post-stimulation in a conjunction search task, suggesting that this brain region may be recruited. This behavioural finding was later replicated in a follow-up experiment (Ellison et al., 2014). The authors found no effect of anodal stimulation. On the other hand, Roy et al. (2015) found that anodal stimulation to the RPC (hereafter, ARPC) reduced RT when targets (an arrow pointing either left or right) were invalidly spatially cued, as indicated by an asterisks appearing on the opposite side to where the target was pointing towards. Thus, in this study anodal tDCS counteracted the normally observed negative impact of invalid spatial cueing.

Further to this, studies have shown that tDCS in healthy subjects can induce temporary deficits that resemble those observed in hemispatial neglect patients. Alternatively, these studies could be interpreted in the reverse, as an enhancement of attention. For example, Roy et al. (2015) found that during ARPC, targets that appeared in the right visual field were neglected slightly, as demonstrated by an increase in RT, compared to targets that appeared in the left visual field. In line with this result, Sparing et al. (2009) found that ARPC enhanced attention and facilitated target accuracy towards the contralateral hemifield, whilst CRPC had the opposite effect and inhibited target accuracy. Line bisection tasks have also been shown to be affected by tDCS, with several research groups replicating a rightward shift in midline judgement after ARPC tDCS (Benwell et al., 2015; Giglia et al., 2011). Overall these effects show that RPC tDCS may induce temporary effects that resemble behaviours

similar to those exhibited by hemispatial neglect patients, as reflected by RT, accuracy or midline judgement biases towards or away from the contralateral side of space.

The evidence regarding the role of the RPC in allocation of attention indicates that this area may be a candidate region involved in probability cueing – an attentional effect that relies heavily on efficiently biasing search towards a cued hemispace. This concept was explored further by investigating RPC stimulation and its interaction and with probability cueing tasks conducted under visual search (Experiment 5), virtual search (Experiment 6) and laboratory search (Experiment 7) constraints.

It is, however, important to note at this stage that the predictions and evidence that these experiments were developed from were centred around examining attention during pure, 2D visual search tasks. The latter experiments in this Chapter use 3D environments, and in Experiment 7, the interaction between RPC stimulation and full-body, physical search is explored. A saccadic bias, developed via the priming of the superior colliculus (Geng & Berhmann, 2002) may hardly be expected to underlie cueing in foraging-type searches because of the effort, physicality and the required use of head and body movements in such tasks, suggesting that these task demands may recruit higher order brain regions (Smith et al., 2010). Further, neuroimaging studies have identified that the RPC engages during virtual environment tasks requiring similar spatial attention demands as real-world search tasks (Hampstead et al., 2014; Maguire et al., 1997; Spiers & Maguire, 2006). These concepts are

discussed further in Experiment 6 and 7, but firstly, a brief discussion on the commonalities between the experiments follows.

5.2 tDCS in the current research

One issue that has recently been highlighted in the field of tDCS is that there is a lack of consistency across published studies regarding the parameters used and the experimental designs undertaken, including: online/offline stimulation protocols, electrode montages, stimulation length and stimulation strength (Horvath et al., 2014; Horvath et al., 2015; Krause & Kadosh, 2014). This makes the conclusions drawn across multiple experiments from different research groups hard to compare. It is also difficult to design studies that have testable predictions when the parameters are vastly mixed. Furthermore, there has been recent criticisms that many studies lack large enough sample sizes to draw accurate and valid results (Berryhill et al., 2014; Horvath et al., 2014). The stimulation parameters of the following three experiments were consistent across a variety of factors: stimulation time, stimulation strength, experimental groups tested, electrode shape, electrode size, electrode montage and experimental design.

tDCS was delivered using a battery-operated, constant current Newronika HDC-Stim (part of the HDC-Kit, Milano, Italy) and using a pair of saline soaked electrode sponge pads. 15 minutes of 1mA stimulation was used. 1mA of current strength is commonly used and is considered a safe stimulation level (Nitsche et al., 2008; Ruffini et al., 2013). Furthermore 1mA has been used in previous studies to investigate the effects of tDCS on visual search tasks, and has demonstrated

significant effects (e.g. Ball et al., 2013; Ellison et al., 2014). The current was ramped up at the beginning of the session for 30 seconds, and ramped down at the end of the session for 30 seconds to avoid 'startle-like' effects (Nitsche et al., 2008).

The RPC was stimulated using anodal and cathodal stimulation, whilst the reference electrode was consistently placed on the LPC. The RPC and LPC were measured using the international 10:20 electrode system (Homan, Herman, & Purdy, 1987), and the electrodes were positioned over P3 (RPC) and P4 (LPC). The active and reference electrode were both rectangular and the sizes were $45cm^2$ (active) and $85cm^2$ (reference). The small electrode size focused the current flow underneath the electrode site, rendering a current density of $0.022mA/cm^2$ – a density large enough to induce cortical change at the point of scalp contact (Nitsche et al., 2007). The larger electrode size, on the other hand, rendered stimulation to the LPC functionally inefficient by dispersing the current flow (Manuel, David, Bikson, & Schnider, 2014; Nitsche et al., 2007) as well as keeping current density at a level smaller enough ($0.012mA/cm^2$) to not induce cortical excitability changes (Nitsche & Paulus, 2000; Nitsche et al., 2007). The active and the reference electrode were both secured using a tight neoprene cap. Hair was parted as much as possible to ensure that contact with the scalp was maximised. Approximately 20ml of saline was used to soak each electrode sponge pad.

The positioning of the electrodes was the same in the Sham group (i.e. LPC-RPC). For this group, the current was ramped up over 30 seconds, followed by 27 seconds of real stimulation and a ramp down of 30 seconds. This sham procedure has previously been shown to be an effective control condition (Gandiga, Hummel, &

Cohen, 2006) by replicating the cutaneous sensations individuals report during active stimulation. Sham stimulation allows for tDCS effects to be more accurately compared to a baseline, control level rather than a simple comparison between the two polarities that are predicted to have effects on performance (Horvath et al., 2014). Electrode positioning is shown in **Figure 5.1**.



Figure 5.1 RPC/LPC tDCS set-up. Electrodes were attached using a rubber cap, but for illustrative purposes they are shown with rubber straps.

A single-blind between-subject design was used for each experiment. A between-subjects design was chosen as probability cueing can withstand interference and can be maintained over a long period of time (Jiang et al., 2012). Thus, a within-

subjects design would not have been suitable as learning could have carried over to the next testing session. Disentangling learning effects and stimulatory effects are also difficult for within-subjects designs, when the task encompasses practice effects (Berryhill et al., 2014). The tDCS machine displayed an identical code, no matter whether sham or active stimulation was undertaken. A single-blind design was chosen as previous research has demonstrated that participants are not sensitive to single-blinding or double-blinding in tDCS experiments (Coffman et al., 2012). To ensure that blinding was efficient, participants were asked at the end of the testing session whether they believed that they had received active (CRPC/ARPC) or inactive (Sham) stimulation.

Avoiding and monitoring tDCS side effects

Before attending any experimental session and continuing with recruitment, volunteers were sent an Information Sheet detailing the experimental procedure and the tDCS set-up, as well as the Screening Questionnaire (**Appendix 1**). The Screening Questionnaire was used to identify whether the individual was at risk of experiencing side effects from active tDCS or whether they should not participate due to health or physical reasons. Volunteers were required to send the tDCS Screening Questionnaire back to the Experimenter before continuing with recruitment. Individuals did not continue with recruitment if: there was a chance they were pregnant, they had a medical diagnosis of a psychological or a neurological condition which requires medication, they had a history of migraines, if contact with the scalp was not possible (e.g. they wore a head scarfs or had dreadlocks), they had any metallic implants, they had a skin or scalp condition, they had experienced a head injury resulting in a loss of

consciousness that required further investigation, they had experienced a seizure or were on any prescriptive medication (apart from the contraceptive pill or implant).

Volunteers were also unable to continue with recruitment if they had participated in any other probability cueing studies. Individuals were also aware that they could receive active or inactive stimulation and were informed about the potential side effects of tDCS (e.g. mild headache, an itching sensation during stimulation). If an individual passed the tDCS Screening Questionnaire, did not meet any exclusion criteria and was happy to continue, a convenient time to attend an experimental session was arranged.

The tDCS Experiment Questionnaire (**Appendix 2**) was completed by each participant before and after a period of tDCS. The questionnaire was completed even if the participant was experiencing sham stimulation. It was used to monitor any side effects attributed to tDCS stimulation during the experiment. The questionnaire contained symptoms reported previously as side effects of tDCS stimulation (Brunoni et al., 2011; Poreisz et al., 2007) as well as pseudo, control items. Participants were asked to rate 'truthfully' whether a symptom applied to them at present and if so how strongly they felt it was on a scale of one (absent) to ten (severe), and if any rated a real symptom above five, they were made aware that their symptom could be exasperated and were advised to withdraw.

5.3 Experiment 5: RPC tDCS and visual search

This experiment investigated whether stimulation to the RPC would interact with probability cueing in visual search. Participants were required to search for a target that was hidden amongst distractors and, unbeknownst to them, the target appeared more frequently on one side (cued trials) of space than the other (uncued trials). They completed six blocks of probability cueing trials. RT for cued and uncued trial was recorded.

It was predicted that, at a general level, stimulation to the RPC would cause an imbalance in activity between the two hemispheres and would manifest as polarity-specific enhancements or decrements to the rate of learning. Participants in the ARPC condition would be more efficient during cued trials (i.e. faster RT), than those in the CRPC group, who would be slower at learning cued trials. Participants receiving sham stimulation would demonstrate probability cueing, but to a lesser degree than the ARPC group, and to a greater degree than the CRPC group. This would manifest as gradual bias in RT to the cued side over time. At a more specific level, it was predicted that tDCS would interact with the cued hemispace, especially when it was on the left side, as this side was contralateral to stimulation. Thus, when the cued hemifield was on the left, it was predicted that participants in the ARPC group would be significantly faster at responding to the cue than when it was on the right. Alternatively, when the cued hemifield was on the left side, a greater impairment in probability cueing would be observed compared to when it was on the right side for the CRPC group. The Sham group would show no hemispatial biases, in line with

other visual search studies (e.g. Geng & Berhmann, 2002) and other experiments in this Thesis. General and specific predictions are illustrated in **Figure 5.2**.

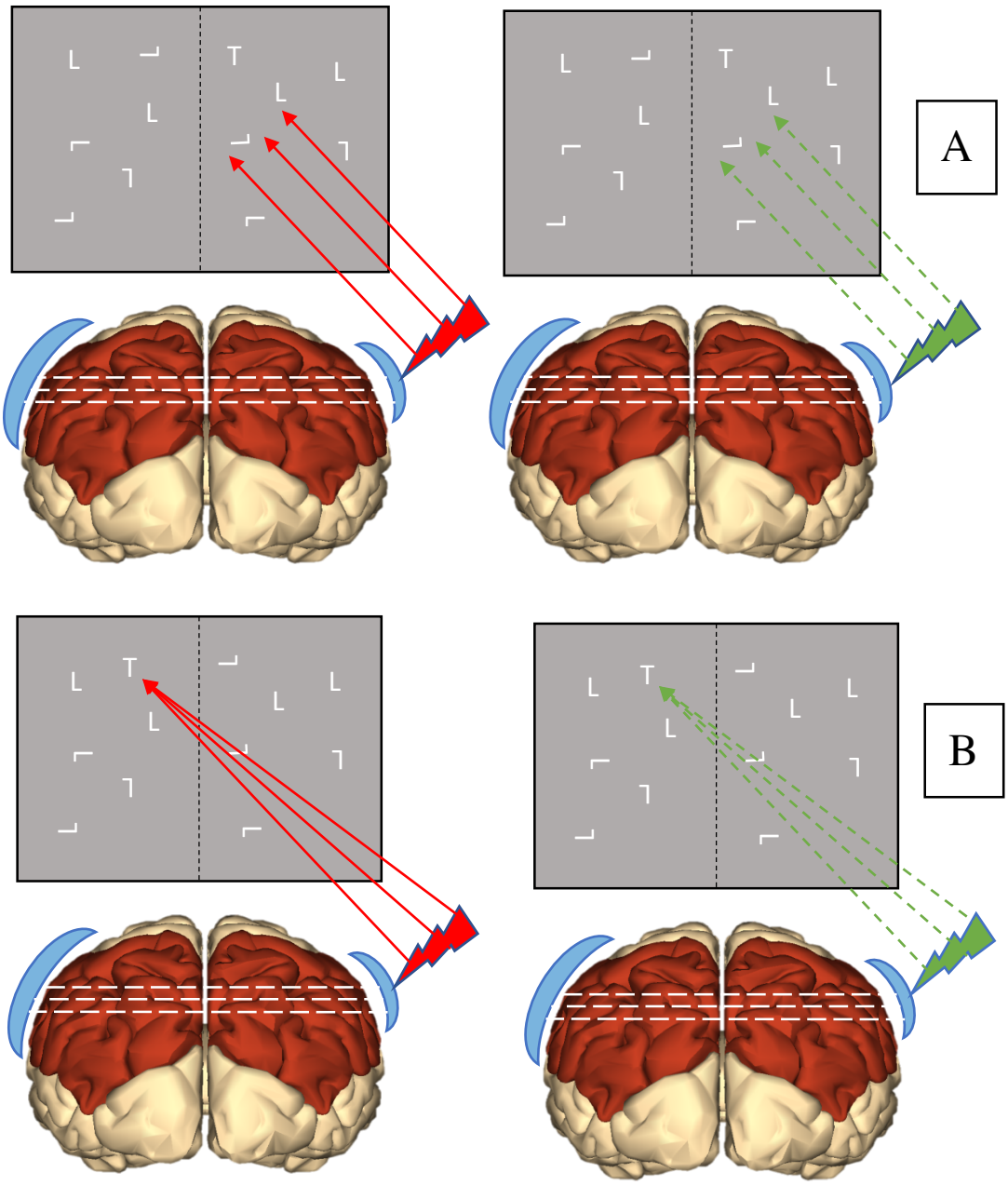


Figure 5.2 ARPC is portrayed by red; CRPC is portrayed by green. **A:** General predictions: ARPC will enhance probability cueing; CRPC will slow probability cueing. Arrows are spread to indicate a global change to RT on cued trials. **B:** Specific predictions: ARPC will enhance search when the cue is on the left and CRPC will slow search when the cue is on the left.

In the stimulation conditions (ARPC/CRPC), tDCS was applied in the first three blocks (i.e. online stimulation) and no current was delivered in the final three blocks (i.e. offline stimulation). Research has shown that the effects of tDCS can outlast its application, inducing temporary 'offline' effects that can last up to 90 minutes (Clark et al., 2012; Nitsche & Paulus, 2001). There has been a limited amount of studies that have investigated whether the offline effects of tDCS can be replicated after RPC stimulation (e.g. Ball et al., 2013; Filmer et al, 2015). It is thought that the mechanisms involved in online and offline tDCS are mediated in different ways, with online stimulation inducing a direct alteration within the membrane potential of the cells under the electrode pad, whereas offline stimulation induces synaptic plasticity effects in the GABA and glutamate systems (Stagg & Nitsche, 2011).

After the probability cueing task, participants were probed about their awareness of the cue using the same questioning as in Experiment 1B[1]. Previous visual search tasks suggest that the probability cue is learnt without awareness, incidentally, and this has also been conveyed by hemispatial neglect patients (Geng & Berhmann, 2002). Furthermore, fMRI experiments have also confirmed that when targets are not consciously detected by hemispatial neglect patients, areas of the damaged RPC are still activated (Rees et al., 2002). This suggests that even though the RPC is damaged (or modulated using tDCS), target detection may originate in this brain region. Therefore, despite temporary tDCS-induced behaviour changes parallel

[1] Experiment 1B questions were used here due to the order that the chronology in which experiments were conducted.

to hemispatial neglect, it was hypothesised that learning would be below conscious level and that tDCS would not influence this.

5.3.1 Method

5.3.1.1 Participants

In total, 77 volunteers were recruited however five participants were unable to continue with the study – three due to tDCS technical malfunctions, one due to difficulties with the task instructions, and one due to previous participation in a probability cueing experiment. Therefore 72 participants[2] were included in the final data analysis. Twenty-four participants were randomly assigned to each experimental group. None of the participants met the exclusion criteria (**Section 5.2**).

The age of the participants ranged from 18 to 34 years (M = 22.81, SD = 2.99) and there were 35 females in the sample. All participants had normal to corrected normal vision and, as recorded by the EHI, 66 were right handed (M = 81.89; SD = 17.02) and six were left handed (M = -50.83, SD = 34.84). Participants received £7 in exchange for 50 minutes of their time.

[2] The most basic design was a mixed ANOVA comparing *trial type* (two levels) and *group* (three levels), with 20 participants per group. A priori power analysis showed a power of 0.99 to detect a large effect (f = 0.40, α = 0.05, df = 1, 57) or 0.97 to detect a medium effect (f = 0.25, α = 0.05, df = 1, 57) for the within-subject factor, *trial type*. For the between-subject factor, *group*, a power of 0.87 was produced to detect a large effect (f = 0.40, α = 0.05, df = 2, 57) or 0.48 to detect a medium effect size (f = 0.48, α = 0.05, df = 2, 57). Although the power to detect this between-subjects main effect is relatively low, the power to detect any interaction between the two factors is considerably greater: 0.99 to detect a large effect (f = 0.4, α = 0.05 0.05, df = 2, 57) or 0.93 to detect a medium effect size (f = 0.25, α = 0.05, df = 1, 57). For Experiments 5, 6 and 7, the aim was therefore to test 20 participants per group to achieve this power.

5.3.1.2 Materials

The task used in this experiment was adapted from the task used by Jiang and Swallow (2013). Participants were required to complete a simple visual search task by making an orientation judgement regarding the letter 'T' target, that was presented amongst letter 'L' distractors. The task was presented in PsychoPy2 (Peirce, 2009), using a Stone Desktop computer running Windows 7. Participants were seated centrally, approximately 60cm away from the monitor screen. Each trial contained 12 items, with one target and 11 distractors. There were 36 possible locations for the target and distractors to appear within, which were formed by dividing the full-screen monitor display into a grid of six vertical columns and six horizontal rows. This grid was further separated into four, smaller quadrants in which three items appeared on each trial. This ensured that an even amount of space was sampled across the course of the experiment and that no items appeared on the midpoint. This created a unique set of random array configurations of the target and the distractors. Neither the large grid nor the quadrants were visible during the trials.

The 'T' was presented either upright (0˚ rotation) or inverted (180˚ rotation). The target appeared on every trial and its rotation was counterbalanced equally across the course of the trials. The distractors were presented at: 0˚, 90˚, 180˚, or 270˚ rotation. Overall the various orientations and similarity between the target and distractors engendered a relatively effortful, serial, self-terminating search (Wolfe, 1998). All items were presented in Ariel font, white colour (RGB: 255, 255, 255) on a grey (RGB: 160, 160, 160) background and were displayed at a viewing angle of 0.80˚.

Each trial began with a fixation cross that appeared in the centre of the screen (subtending 0.10 visual angle). The fixation cross appeared on the same grey background as the visual search display and was displayed in white (RGB: 255, 255, 255) Ariel font. Participants were asked to focus their attention on this fixation cross when it was on the screen. After 800ms, the fixation cross disappeared and the visual search display was initiated.

Participants completed six blocks of 80 trials, totalling 420. Unbeknownst to them, the target appeared 80% of the time in one hemifield ('cued side') and 20% of the time in the other ('uncued side'). This meant that within each block, the target appeared on the cued side in 64 trials, and 16 trials on the uncued side. The target could repeat in its location across trials. Target location repetitions occurred randomly within 2% of total trials (30240 trials across all participants). The cued side was counterbalanced, so that 12 participants were randomly assigned the cue on the left and 12 participants were randomly assigned the cue on the right per experimental group.

5.3.1.3 tDCS protocol

The tDCS protocol was the same as that described in **Section 5.2**. ARPC, CRPC and Sham tDCS was examined, with the active groups receiving 15 minutes of 1mA current. Sham participants received 15 minutes of no stimulation, but at the beginning the current was ramped up, followed by a 27 second stimulation interval and ramped down for 30 seconds.

Each participant completed the first three blocks of trials (Block 1, Block 2, Block 3) with the tDCS electrodes on. Between Block 3 and Block 4 the tDCS was ramped down, and each participant completed the final three blocks (Block 4, Block 5, Block 6) with tDCS deactivated. This created a set of 'online' stimulation blocks (first 240 trials) and 'offline' after-effects blocks (second 240 trials), lasting 15 minutes per three blocks. This was done so that the after-effects of tDCS could be studied, as well as any behavioural changes during online stimulation. Between each block, participants were instructed to wait until the Experimenter told them to begin. This ensured that each block lasted 5 minutes, so that it could be accurately timed with the stimulation. On average, each individual block was completed in approximately 4 minutes, meaning participants had a short interval of approximately 1 minute between the end and start of new block. In total, the visual search task took 30 minutes, with a 15-minute online phase and a 15-minute offline phase.

5.3.1.4 Procedure

Once seated, participants were briefed and they signed a Consent Form and completed the tDCS Experiment Questionnaire. Following this, the electrode positions (RPC/LPC) were measured and marked on the participants scalp using a washable marker. After parting the hair sufficiently, the saline soaked sponge pads containing the electrodes were secured to the scalp using a neoprene cap. Once the participant was comfortable, the tDCS was started and after 30 seconds of ramp up, the participant was asked to press the space bar to begin the task. The participant was informed when the tDCS was switched on.

The first three blocks of the visual search task then proceeded, during which the participant received active or sham stimulation for 15 minutes (online period). Participants were asked to make a keypress based on the orientation of the 'T'. If it was upright (0° rotation) they were asked to press the letter 'A' with their left index finger, and if it was inverted (180° rotation) they were asked to press the letter 'L' with their right index finger. The visual search display remained on the screen until a response was made. After 80 trials, a message appeared telling the participant to stop. They were then required to wait until the timer reached 5 minutes and the Experimenter instructed them to continue. The next 80 trials were initiated by pressing the space bar. This procedure was repeated three times. The participant then completed another three blocks of 80 trials without tDCS (offline period). If the participant was receiving active stimulation, the machine was ramped down for 30 seconds before they continued the final three blocks.

After completing all 480 trials, participants were probed for their awareness of the probability cue using the same Post-Experiment Questions as described in Experiment 1A (**Section 3.2.2.2**). Participants were asked whether they used a strategy, whether they had a sense of the target's location and were then presented a forced-choice probe regarding the cued side. Following this, participants were given another copy of the tDCS Experiment Questionnaire, the SBSODS and the EHI. They were then asked to sign a Post-Experiment Checklist that asked whether they believed they had received active or inactive stimulation, and to confirm that any unpleasant feelings had dissipated. Participants were debriefed. The whole procedure was approximately 50 minutes.

5.3.2 Results

Handling RT data

Compared to the other experiments reported in this Thesis, the RTs generated in Experiment 5 were much shorter, meaning tDCS effects may be subtler. RT were therefore subject to some potential concerns. RT data tends be asymmetrically distributed (Cousineau & Chartier, 2010) and positively skewed (Ratcliff, 1993; Whelan, 2008), meaning that data points tend to lie towards the right of zero with a long tail, and rise rapidly on the left (Field, 2013). In turn, this means that RT data more accurately fits an ex-Gaussian distribution, rather than the Gaussian distribution (Whelan, 2008). An ex-Gaussian distribution consists of three parameters, as demonstrated by the raw data from Experiment 5 in **Figure 5.3**: mu (mean of the rise on the left), sigma (standard deviation of the rise on the left) and tau (mean and standard deviation of the positively skewed tail on the right) (Ratcliff, 1993; Whelan, 2008). RT data violates the assumptions of many parametric tests, such as ANOVA, in which data should only be entered in such statistical models if it is normally distributed (Field, 2013) – although, paradoxically, it is the most common method for analysing RT data (Whelan, 2008).

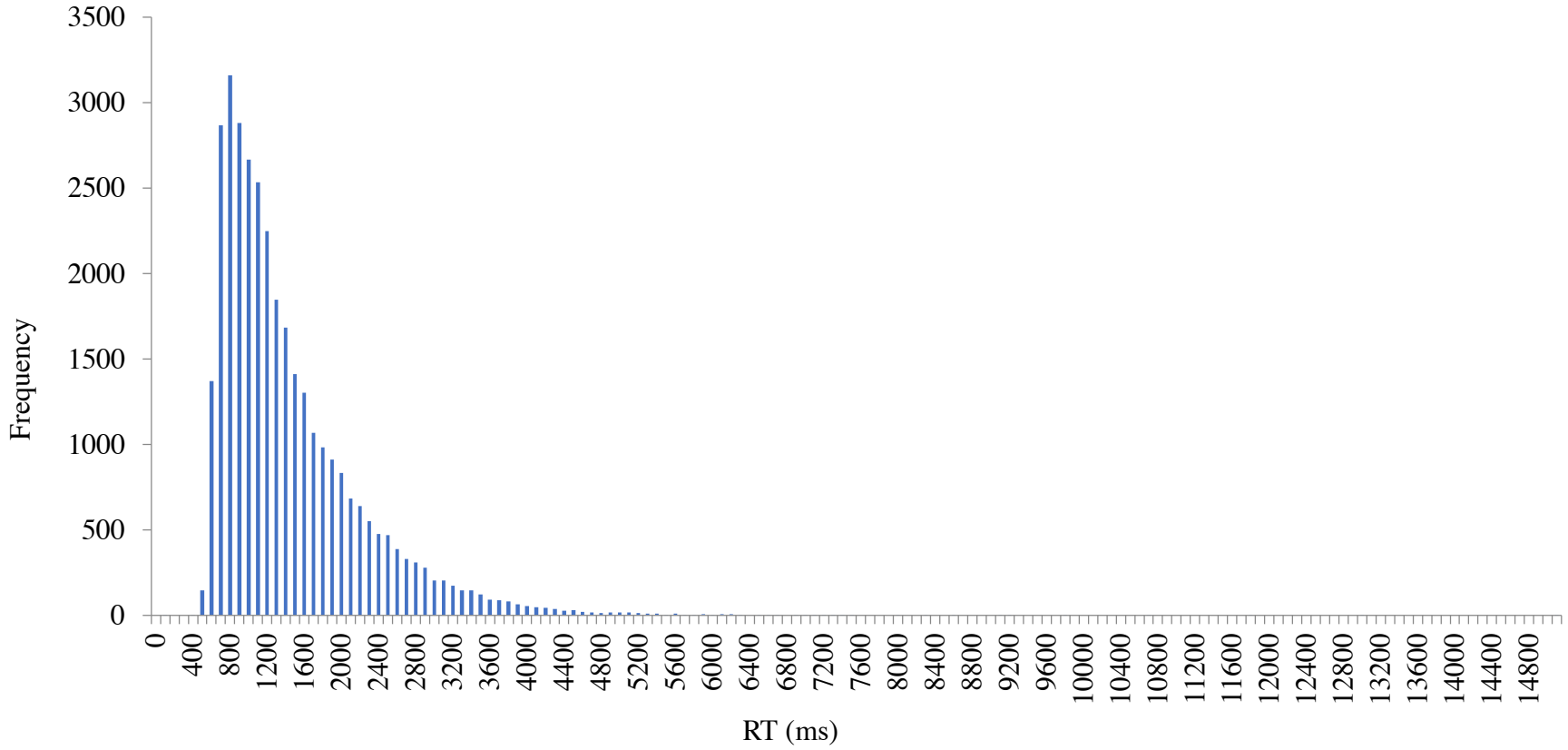


Figure 5.3 Histogram illustrating the raw data in Experiment 5.

There are a variety of methods that can be used to normalise RT data, as well as dealing with outliers, and these range from trimming data to using central tendency measures. For this experiment, data was log transformed. This is an effective method for dealing with the positive skew and kurtosis (Field, 2013). There are, however, some issues associated with data transformations. For example, it has been argued that it is difficult to draw conclusions from such data as it is not the same as the raw data and the relationship between the variables has changed (Field, 2013). In the case of log transforms, it also means that the hypothesis being tested has been adjusted, as geometric means are now being compared rather than arithmetic means (Games, 1984). Transforming data may also make it difficult to compare results to previous published literature, if authors have not transformed their data too (Bush, Hess, & Wolford, 1993). Applying the wrong transformation could also be more disastrous than applying no transform at all. It could be that null results or unpublished data has occurred due to inappropriate transformations – or the reverse, in which raw data without appropriate transformations may be assumed non-significant. Some researchers have suggested that it is advisable for both transformed and untransformed data to be reported to avoid this (Bush et al., 1993).

Although caution should be applied when transforming data, the benefits may outweigh the risks, such as enhancing linearity, improving the fit of the data to a Gaussian shape, reducing positive skew and kurtosis (Field, 2013). Furthermore, transforming data is standardised, unlike more popular methods such as trimming data, in which a restricted mean is created that is not necessarily an accurate representation of the raw, unrestricted data set (Van Selst & Jolicoeur, 1994). There is

no reliable rule, with trimming values varying greatly (Miller, 1991). If data violates assumptions of parametric tests, then transformations may help increase power (Ratcliff, 1993) by reducing huge variability amongst RTs recorded from different subjects (Bush et al., 1993).

Pre-analysis

Analyses were conducted using trials in which the orientation of the 'T' was reported correctly. This resulted in a total of 97.74% of correct trials in the analysis. When divided into each of the respective experimental groups, percentage of correct trials were near ceiling (ARPC: M = 97.47%, SD = 2.08, CRPC: M = 97.89%, SD = 1.90, Sham: M = 97.86%, SD = 1.46). Groups did not differ in their accuracy ($F < 1, f$ = 0.10) Any values less than 200ms or above 10000ms were excluded from the dataset (a total of 0.02% of data)[3]. Finally, all RTs were log transformed. The final distribution of the data is in **Figure 5.4**.

[3] These cut-offs were chosen as it has been demonstrated that the physiological processes involved in producing a **genuine** response (i.e. stimulus perception, motor movement), rather than a fast guess, need a minimum of between 100ms to 200ms (Luce, 1986). One participant accidently pressed the space bar before the Experimenter told them to proceed, hence the cut-off of 10000ms. Other probability cueing studies have also used this as a higher cut-off point (e.g. Jiang & Swallow, 2013)

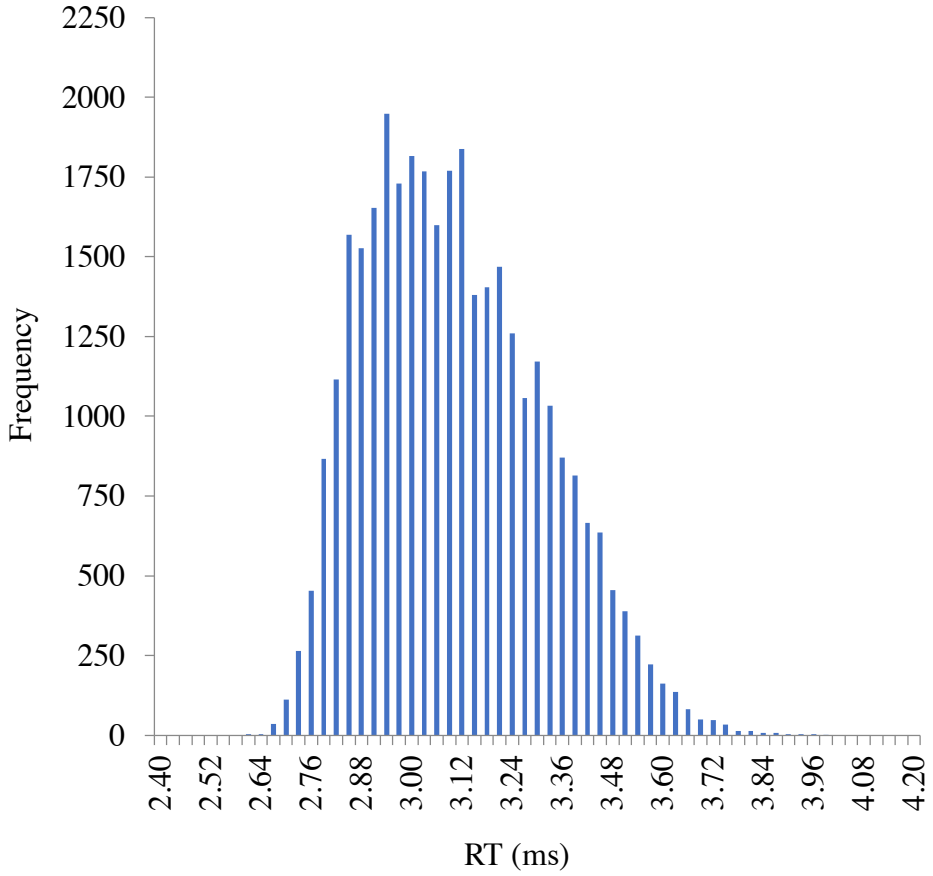


Figure 5.4 Histogram illustrating the log transformed data for Experiment 5.

5.3.2.1 Behavioural results

A mixed ANOVA[4] was conducted on the log transformed RT data, comprising of the factors: *block* (within-subjects factor; six levels: Block 1, Block 2, Block 3, Block 4, Block 5, Block 6), *group* (between-subjects factor; three levels: ARPC, CRPC, Sham), *trial type* (within-subjects factor; two levels: cued, uncued) and *cued side* (between-subjects factor; two levels: left, right). This revealed a main effect of

[4] In previous experiments, the cued side was not included in analysis. For Experiments 5-7, the cued side is deemed important as it could interact with tDCS producing hemifield biases (outlined in the specific hypotheses).

trial type ($F(1, 66) = 810.05$, $p < 0.001$, $f = 3.51$), indicating that RT to cued targets ($M = 3.06$ms, $SD = 0.66$) was significantly faster than uncued targets ($M = 3.21$ms, $SD = 0.65$). Mauchley's test indicated that the assumption of sphericity had been violated for block ($\chi^2(14) = 39.65$, $p < 0.001$), therefore Huynh-Feldt[5] estimates of sphericity were reported ($\tilde{\varepsilon} = 0.87$). There was a main effect of block ($F(4.35, 287.13) = 102.93$, $p < 0.001$, $f = 1.25$). Means and standard deviations for this main effect, as well as per trial type, per block are displayed in **Table 5.1**. Pairwise Comparisons revealed significant differences in RT across the blocks as the experiment progressed ($p < 0.05$), apart from borderline significance between Block 3 and Block 4 ($p = 0.057$), and no significant difference between Block 5 and Block 6 ($p > 1.00$). A full list of values from these comparisons is in **Appendix 4**.

Table 5.1 Means and standard deviations for RT (ms) per block, per trial type, and overall.

	Block 1	**Block 2**	**Block 3**	**Block 4**	**Block 5**	**Block 6**
Cued trials	$M = 3.14$, $SD = 0.07$	$M = 3.09$, $SD = 0.07$	$M = 3.06$, $SD = 0.08$	$M = 3.04$, $SD = 0.07$	$M = 3.02$, $SD = 0.07$	$M = 3.01$, $SD = 0.07$
Uncued trials	$M = 3.24$, $SD = 0.08$	$M = 3.22$, $SD = 0.08$	$M = 3.21$, $SD = 0.07$	$M = 3.21$, $SD = 0.08$	$M = 3.20$, $SD = 0.08$	$M = 3.19$, $SD = 0.07$
Overall	$M = 3.19$, $SD = 0.07$	$M = 3.15$, $SD = 0.07$	$M = 3.14$, $SD = 0.07$	$M = 3.12$, $SD = 0.07$	$M = 3.11$, $SD = 0.07$	$M = 3.10$, $SD = 0.06$

There was a significant interaction between trial type and block ($F(5, 330) = 27.43$, $p < 0.001$, $f = 0.65$). This interaction effect is plotted in **Figure 5.5**. As recommended by Field (2013), Simple Effects Analysis was carried out on this interaction (Pairwise Comparisons, Bonferroni-corrected). The first analysis

[5] Huynh-Feldt estimates are reported for this main effect as Greenhouse-Geisser estimate >0.75 ($\varepsilon = 0.77$). If it is above this threshold, results may be too conservative (Huynh & Feldt, 1970).

demonstrated a significant effect of block at each level of trial type (cued trials: $p < 0.001$; uncued trials: $p < 0.001$). However, closer examination of the Pairwise Comparisons of these effects, revealed that some comparisons did not reach significance. To elaborate, on cued trials, there was a significant difference in RT ($p < 0.05$) across all blocks apart from Block 5 and Block 6 ($p = 0.299$), in which RT stabilised. In comparison, there was no significant difference in RT on uncued trials in: Block 1 and Block 2 ($p = 0.167$), Block 2 and Block 3 ($p > 1.00$), Block 2 and Block 4 ($p = 0.245$), Block 3 and Block 4 ($p > 1.00$), Block 3 and Block 5 ($p = 0.442$), Block 4 and Block 5 ($p > 1.00$), Block 4 and Block 6 ($p = 0.908$), Block 5 and Block 6 ($p > 1.00$). All other comparisons were significant ($p < 0.05$). Thus, RT on cued trials become progressively faster across the blocks, whereas there was little difference for RT on uncued trials across the blocks. A full list of values from these comparisons is in **Appendix 5.**

The second analysis showed that there was a significant effect of trial type at each level of block ($p < 0.001$), with cued trials responded to quicker than uncued trials in Block 1 ($p < 0.001$), Block 2 ($p < 0.001$), Block 3 ($p < 0.001$), Block 4 ($p < 0.001$), Block 5 ($p < 0.001$) and Block 6 ($p < 0.001$).

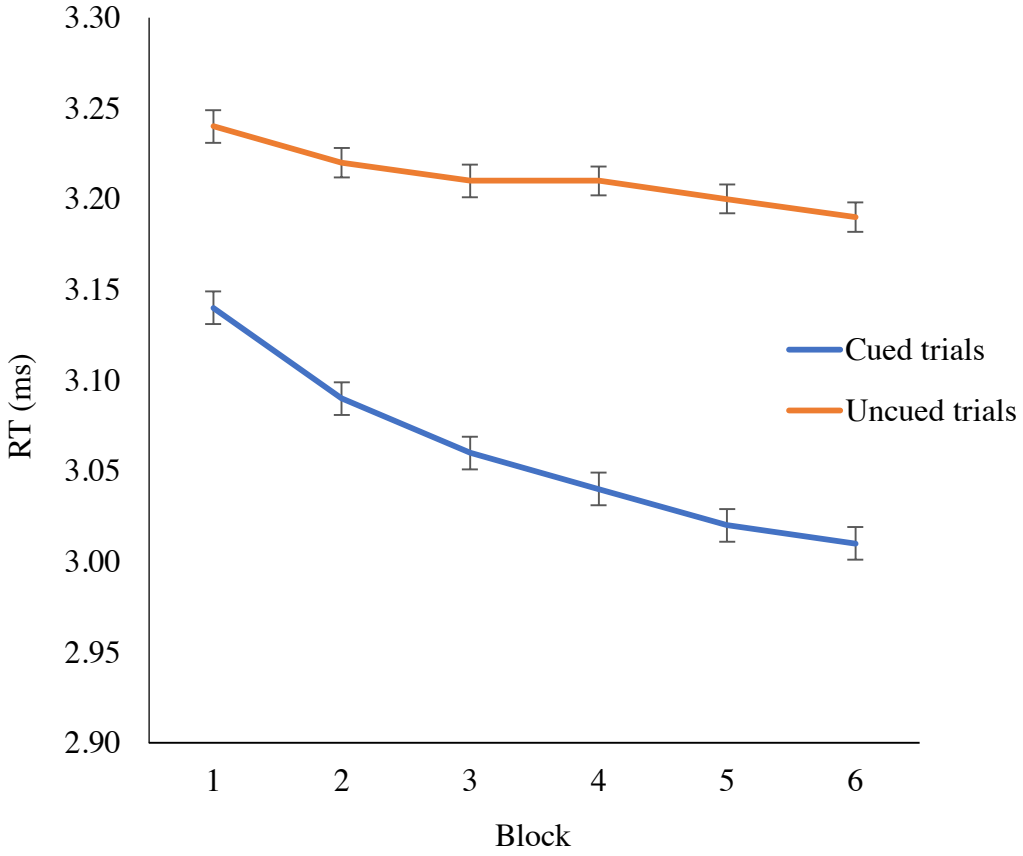


Figure 5.5 Significant trial type x block interaction. As the trials progressed, cued trials incurred speedier responses than uncued trials. Error bars represent +/-1 standard error of the mean.

There was also a main effect of group ($F(2, 66) = 3.42$, $p = 0.039$, $f = 0.32$). Pairwise Comparisons (Bonferroni-corrected) revealed that the ARPC group (M = 3.12ms, $SD = 0.10$) were significantly faster ($p = 0.048$) than CRPC (M = 3.16ms, SD = 0.11). However, the Sham group (M = 3.13ms, SD = 0.11) did not significantly differ in their RT to either ARPC ($p > 1.00$) or CRPC ($p = 0.154$). These results are illustrated in **Figure 5.6**.

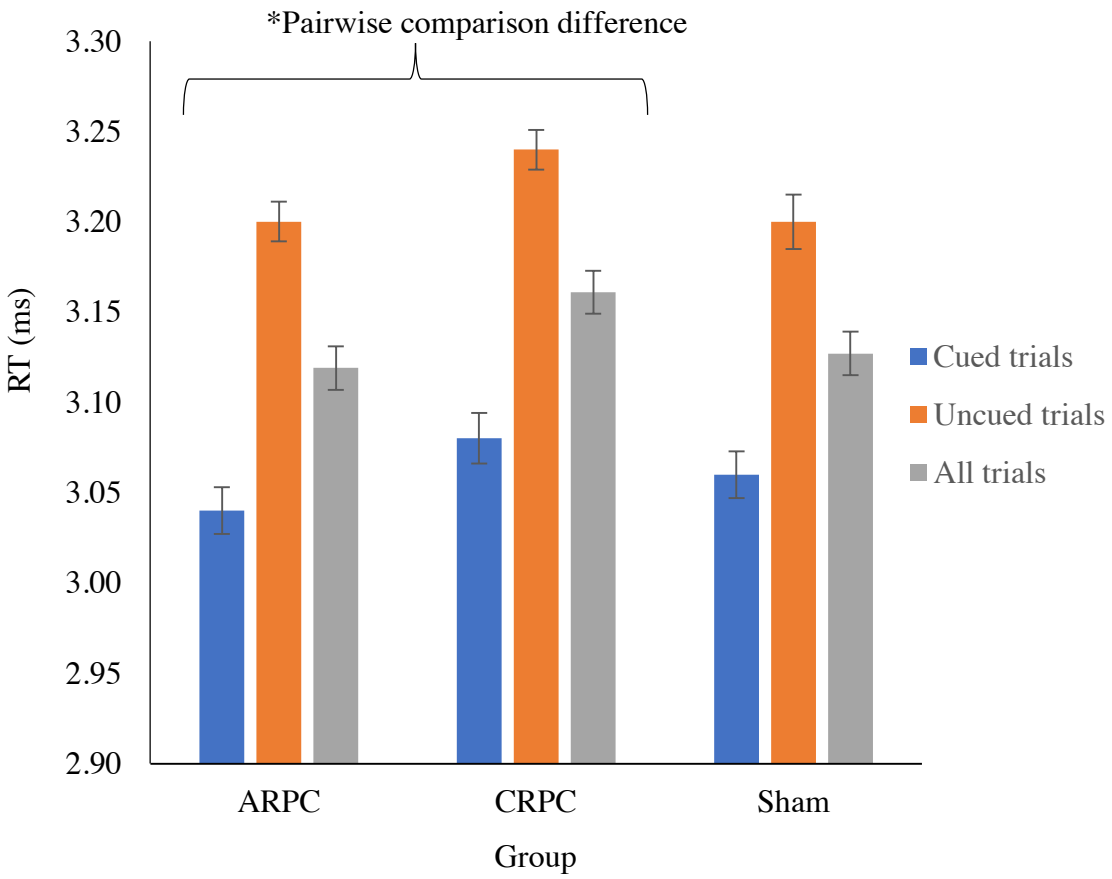


Figure 5.6 RT for cued, uncued and all trials. ARPC were significantly faster at completing the task than CRPC. Error bars represent +/-1 standard error of the mean, *$p < 0.05$.

There was no significant main effect of cued side ($F(1, 66) = 2.00, p = 0.162, f = 0.17$) indicating that responses did not differ when the cue appeared more frequently on the left side ($M = 3.15$ms, $SD = 0.06$) or right side ($M = 3.13$ms, $SD = 0.06$) of the array. There was, however a significant interaction between trial type and cued hemispace ($F(1, 66) = 7.38$, $p = 0.008$, $f = 0.34$). The first Simple Effects Analysis, examining the cued side at the levels of trial type, showed that was no significant difference ($p = 0.747$) between cued trials when the cued hemispace was

designated to the left (M = 3.06ms, SD = 0.06) or the right (M = 3.06ms, SD = 0.07). In comparison, there was a significant effect (p = 0.024) on uncued trials. This significant effect therefore suggested that responses were faster on uncued trials when the *uncued* hemispace was assigned to the left side (M = 3.23ms, SD = 0.06) rather than the right side (M = 3.20ms, SD = 0.07).

The next analysis examined the effect of trial type at both levels of cued side. For both levels, this was significant (left: $p < 0.001$; right: $p < 0.001$). When the target appeared more frequently on the left, RT was faster on cued trials (M = 3.06ms, SD = 0.06) than uncued trials (M = 3.23ms, SD = 0.06). These results were reflected when the target appeared more frequently on the right (cued trials: M = 3.06ms, SD = 0.07; uncued trials: M = 3.20ms, SD = 0.07).

All other results did not reach significance including: the interaction between block and group ($F < 1, f = 0.11$), trial type and group ($F(2, 66) = 1.20, p = 0.309, f = 0.19$), block and cued side ($F < 1, f = 0.10$) and group and cued side ($F < 1, f = 0.11$). There were no significant three-way interactions between trial type, group and block ($F < 1, f = 0.14$), trial type, group and cued side ($F < 1, f = 0.15$), block, trial type and cued side ($F < 1, f = 0.08$), or block, cued side and group ($F < 1, f = 0.08$). Finally, the interaction between cued side, trial type, block and group was not significant ($F < 1, f = 0.08$).

5.3.2.2 Individual differences

Post-Experiment Questions

43% of participants reported using a strategy. This result did not differ from chance level (*binomial*, $p = 0.289$), suggesting that visual search strategies were uncommon. Across the experimental groups, 42% ARPC, 38% CRPC and 50% Sham participants reported using a strategy. A Chi-square Test[6] was used to compare these responses. This was not significant ($\chi^2(2) = 0.79$, $p = 0.673$, $V = 0.11$) suggesting that there was no association between stimulation type and forming a search strategy.

Of the participants that reported using a strategy, 13% mentioned an awareness of the target's location when asked to detail their strategy (*binomial*, $p < 0.001$). This result suggested that several participants did not acknowledge the target likelihoods. 17% ARPC, 8% CRPC and 13% Sham participants reported some knowledge of the target's location when recording their strategies. Like before, there was no significant association between the stimulation type and the formation of an explicit strategy (Fisher's Exact Test: $p = 0.903$, $V = 0.10$)[7].

Following this question, participants were asked if they had a sense of where the target was most likely to be: 42% of participants reported this (*binomial*, $p = 0.195$). Examining the experimental groups separately, half of the Sham participants

[6] Cramer's *V* is used for effect sizes in Pearson's Chi-square tests. The values fall between 0 and 1, and the magnitude of effect sizes are defined similarly to Cohen's *d* (1988, 1992). *V* effect sizes: 0.1 = small, 0.3 = medium, 0.5 = large.

[7] Fisher's Exact Test is used instead of Pearson's Chi-square test when the expected frequencies in one or more cell are lower than 5, as the Chi-square statistics deviates from the Chi-square distribution and is deemed inaccurate (Field, 2013).

(50%) responded "Yes" to this question. CRPC (42%) were the next group most likely to report having a sense of the target's location, followed by ARPC (33%). Again, there was no significant association between the experimental groups and reporting a sense of the target's location ($\chi^2(2) = 1.37, p = 0.552, V = 0.14$).

25% of participants reported an awareness of the cued side (*binomial*, $p < 0.001$) when they were probed further in Question 2. This result was in the direction of minimal awareness of the cue. 29% of Sham and CRPC demonstrated an awareness in their answers, whilst 16% of ARPC did. Again, the stimulation type the participant received did not change their awareness of the cue ($\chi^2(2) = 1.33, p = 0.654, V = 0.14$).

Finally, participants were presented with a forced-choice regarding the cued hemispace. 89% of participants accurately reported the cued side. This was significantly above chance level (*binomial*, $p < 0.001$), and indicated that participants were only able to identify the cued side when explicitly presented with a forced-choice. All ARPC participants (100%) correctly identified the cued side. This was shortly followed by 88% CRPC and 79% Sham participants. Stimulation type was not associated with correctly identifying the cued side of space ($\chi^2(2) = 5.34, p = 0.086, V = 0.27$). All results from the Post-Experiment Questions are displayed in **Table 5.2**.

Table 5.2 Post-Experiment Questions. Many participants accurately identified the target's location when given a force-choice probe, suggesting that learning was below conscious level. ** $p \leq 0.001$

Question	Group	Answer	Result
1A - Strategy *"Did you use a strategy to search for the target in the environment"*	Total	Yes: 43% ($n = 31$) No: 57% ($n = 41$)	*Binomial:* $p = 0.289$, less than 50% chance level.
	ARPC	Yes: 42% ($n = 10$) No: 58% ($n = 14$)	*Chi-Square:* $\chi^2(2) = 0.79$, $p = 0.673$, $V = 0.11$, group had no effect.
	CRPC	Yes: 38% ($n = 9$) No: 62% ($n = 15$)	
	Sham	Yes: 50% ($n = 12$) No: 50% ($n = 12$)	
1B – Strategy *"If YES please explain your strategy"*	Total	Awareness: 13% ($n = 9$) No awareness: 87% ($n = 63$)	*Binomial*: $\mathbf{p < 0.001}$**, in the direction of no awareness of the probability cue.
	ARPC	Awareness: 17% ($n = 4$) No awareness: 83% ($n = 20$)	*Fisher's Exact Test:* $p = 0.903$, $V = 0.10$, group had no effect.
	CRPC	Awareness: 8% ($n = 2$) No awareness: 92% ($n = 22$)	
	Sham	Awareness: 13% ($n = 3$) No awareness: 87% ($n = 21$)	
2A - Sense *"Did you have a sense of where the target was most likely to be in the environment?"*	Total	Yes: 42% ($n = 30$) No: 58% ($n = 42$)	*Binomial*: $p = 0.195$, less than 50% chance level.
	ARPC	Yes: 33% ($n = 8$) No: 66% ($n = 16$)	*Chi-Square*: $\chi^2(2) = 1.37$, $p = 0.552$, $V = 0.14$, group had no effect.

	CRPC	Yes: 42% (n = 10) No: 58% (n = 14)	
	Sham	Yes: 50% (n = 12) No: 50% (n = 12)	
2B – Sense *"If YES please explain your 'sense' of the target's location"*	Total	Awareness: 25% (n = 18) No awareness: 75% (n = 54)	*Binomial*: **$p < 0.001$**,** in the direction of no awareness of the probability cue.
	ARPC	Awareness: 33% (n = 8) No awareness: 66% (n = 16)	*Chi-Square*: $\chi^2(2) = 1.33$, $p = 0.654$, $V = 0.14$, group had no effect.
	CRPC	Awareness: 42% (n = 10) No awareness: 58% (n = 14)	
	Sham	Awareness: 50% (n = 12) No awareness: 50% (n = 12)	
3 - Final probe *"If I told you that the target was more likely to appear on one side, would you be able to guess which one?"*	Total	Correct judgement: 89% (n = 64) Incorrect judgement: 11% (n = 8)	*Binomial*: **$p < 0.001$**,** more participants correctly identified the cued side.
	ARPC	Correct judgement: 100% (n = 14) Incorrect judgment: 0% (n = 0)	*Chi-Square*: $\chi^2(2) = 5.34$, $p = 0.086$, $V = 0.27$, group had no effect.
	CRPC	Correct judgement: 88% (n = 21) Incorrect judgement: 12% (n = 3)	
	Sham	Correct judgement: 79% (n = 19) Incorrect judgement: 21% (n = 5)	

Questionnaire data

As RT was the only measure of spatial learning in this experiment, one cueing effect based on this was calculated. This was calculated by averaging across all the blocks for cued and uncued trials separately, then subtracting the uncued trial average from the cued trial average. The more positive the cueing effect value, the more efficient learning was.

The results from the correlations are outlined in **Table 5.3**. There were no significant relationships between the cueing effect and the EHI, SBSODS and gender ($p > 0.05$). The only result that reached statistical significance was between gender and SBSODS (r_{pb}= -.26, p = 0.026). This relationship was negative, indicating that females scored lower on the SBSODS than males.

Table 5.3 Experiment 5 - Pearson's Product-Moment Correlations (r and α) and a Point-Biserial Correlation (r_{pb} and α) for the cueing effect and questionnaire measures, *$p < 0.05$, **$p \leq 0.001$.

		1.	2.	3.	4.
1. Cueing effect		-			
2. EHI	r	.12	-		
	α	0.315			
3. SBSODS	r	.02	-.16	-	
	α	0.841	0.169		
4. Gender	r_{pb}	.07	.13	**-.26***	-
	α	0.563	0.293	**0.026**	

Sham and active recognition

At the end of the experiment, each participant was asked whether they thought they had received "active" or "inactive" tDCS. In total, 58% of participants were correctly able to identify their tDCS condition. However, this did not reach chance level (*binomial*, $p = 0.195$), suggesting that overall blinding was effective. When divided into the experimental groups, 75% of ARPC participants reported receiving active stimulation. In comparison, 50% of CRPC and Sham participants correctly reported either receiving active or inactive stimulation. The assigned stimulation group was not associated with correct recognition of stimulation type ($\chi^2(2) = 4.11$, $p = 0.128$, $V = 0.24$), suggesting that although a greater percentage of ARPC participants correctly reported active stimulation, across the groups, most participants could not accurately judge their stimulation condition.

5.3.3 Discussion

Probability cueing is demonstrated in visual search paradigms by a bias in RT towards the side of space where a target appears more frequently (Geng & Berhmann, 2002). Although this effect is well-established in the literature (e.g. Geng & Berhmann, 2002; Goshy et al., 2014; Jiang & Swallow, 2013), the underlying neural regions that support this spatial learning process are unknown. This experiment was the first to examine whether the RPC, a brain region that is thought to help allocate attention towards behaviourally relevant stimuli (Bisley & Goldberg, 2010; Corbetta & Shulman, 2002), is involved in probability cueing. This was done so by using an

online and offline tDCS protocol, and modulating the RPC using anodal, cathodal and sham stimulation, during a simple visual search task.

Probability cueing was established: there was a significant interaction between trial type and block, and further statistical analysis showed that within cued trials there was a consistent reduction in RT as the experiment progressed (apart from in Block 5 and Block 6, when attention optimised). RT for uncued trials varied little across the blocks. Instead, RT was consistently quicker when the target was cued compared to when it was on the uncued, across all blocks of trials. This result is in line with data from Kabata and Matsumoto (2012) who found that probability cueing emerged after 80 trials. However, it is important to highlight that in the current data, each block consisted of 80 trials. It would be of interest to see whether probability cueing in visual search emerged even earlier than trial 80. This has been shown before, for example, by Jiang et al. (2015) who found that probability cueing was present after 12 trials, but in this study and the study by Kabata and Matsumoto (2012), the trial sequence was split into blocks without pseudorandomising the cued and uncued trials to occur within each separate block. As detailed before in Chapter 3 (**Section 3.3.3**), this could be problematic for statistical analysis with inaccurate comparisons made across blocks and trial types. In the current experiment, the total trial sequence was divided into separate blocks of 80 trials with 64 cued trials and 16 uncued trials per block. Dividing the current data into smaller epochs would provide a finer analysis of probability cueing, although this analysis would not overcome the caveat of the uneven amount of trial types per block.

A general prediction was made that advocated polarity-specific effects, with ARPC improving probability cueing and CRPC disadvantaging probability cueing. However, results suggested this was not the case. The lack of significance suggests that tDCS did not influence sensitivity to probability cueing; there was no evidence of a polarity-induced imbalance which behaviourally would have been demonstrated by a faster (as induced by ARPC) or slower (as induced by CRPC) RT on cued trials.

On the other hand, a broader tDCS effect was observed, with ARPC participants more efficient at the task than CRPC participants, as demonstrated by a decrease in RT. The CRPC and ARPC group did not differ in RT to the Sham group. This may reflect some of the effects found in probability cueing with neglect patients (Shaqiri & Anderson, 2012). For example, patients could bias their search towards a probabilistic 'hot-spot' area rather than the cued side, suggesting that probability cueing was intact but to a lesser extent. Furthermore, neglect patients learn the probability cue, but overall, are slower at the task than aged matched controls (Geng & Behrmann, 2002). Finally, in virtual clinical tasks, neglect patients show deviating hand movements which are expressed as a general slowness in responding to targets (Broeren et al., 2007). Similarly, to hemispatial neglect patients, in this study, the CRPC group learnt the cue but were generally slower at responding.

The results also indicated that the polarity of the stimulating current affected search across the entire hemifield, rather than contralateral to stimulation. This is contradictory to the specific hypotheses made that were evidenced from several studies that have produced significant contralateral biases in tasks that require spatial attention (e.g. Benwell et al., 2015; Giglia et al., 2011; Roy et al., 2015; Sparing et al.,

2009). There are multiple reasons why this hemifield bias may not have been replicated in this experiment. For instance, the line bisection task used by Sparing et al. (2009), Giglia et al. (2011) and Benwell et al. (2015), requires the participant to detect differences and indicate where the line should be bisected allowing for a thresholding approach to be adopted to identify attention biases. In comparison, the probability cueing paradigm requires the participant to search the environment for the target that is probabilistically defined. Rather than making a forced-choice decision about the respective lengths of the three or four line segments, participants complete an effortful search and adapt their performance according to the spatial distribution. Although the two tasks incur considerable task demand differences, it has been shown that the RPC plays a dominant role in allocating attention during the line bisection task (Fink et al., 2000), hence this may not be the only reason for these differences.

Another point to note is that although stimulation to the RPC has demonstrated hemifield biases, a recurring issue with these experiments is that they differ in the electrode montages used, making valid comparisons difficult. It has been demonstrated that different electrode montages can change the direction of underlying current (Bikson et al., 2010) so that different brain regions receive the active tDCS effects. Moreover, there is also no standardised or universal guidance on stimulation strength or time. These differences make it difficult to ascertain the optimal protocol for a particular task and whether the effects were due to anodal, cathodal or both stimulation types together, across published experiments.

Equal to the present experiment, there has been a study that found no hemifield bias with RPC stimulation. Li et al. (2015) used a dual electrode montage in

which both the LPC and RPC were stimulated with the same size electrodes ($25cm^2$), at 2mA for 30 minutes. They used a modified version of the Posner Cueing Task in which the hemispace of the target was either explicitly validly cued (80% of trials), explicitly invalidly cued (20% of trials) or neutrally cued using arrows before it's appearance. Using these tDCS parameters, and parallel to the results from this experiment, the authors found no interaction between the stimulation and the side that was cued.

However, Li et al. (2015) reported a generic side bias. In all cue conditions, responses were faster when the targets appeared in the left hemifield than in the right hemifield. In the present experiment, when the uncued side was on the participant's left, search was quicker than when the uncued side was on the right. In all other experiments reported in this Thesis, there has not been an effect of the cued side on search performance. Only a handful of experiments have directly examined whether the cued side effects probability cueing (e.g. Buckley & Smith, 2013; Geng & Behrmann, 2002), and have found no effect of this on search performance in healthy subjects. This was tested as neurologically intact subjects demonstrate signs of pseudoneglect which is defined as a slight bias towards the left side of space (Jewell & McCourt, 2000). This bias is most evident on line bisection tasks, where subjects tend to bisect the line more leftwards of the centre point. This finding of a small leftward bias emphasises the importance of counterbalancing the cued side across hemifields, and highlights that further studies should consider the 'cued side' as an important factor in statistical analysis.

Finally, at the end of the experiment, participants completed several questionnaires. SBSODS was found to correlate with gender, with females reporting a poorer sense of direction; a finding that emphasises the potential sex differences navigation (Hegarty et al., 2002; Voyer et al., 2000; Voyer et al., 1995). Participants were also probed about their awareness of the probability cue, and were only able to identify the cued side upon a forced-choice question. tDCS had no effect on conscious awareness. Although many visual search studies simply ask participants if they thought the target appeared equally or unequally (e.g. Geng & Berhmann, 2002; Goschy et al., 2014, Kabata & Matsumoto, 2012), the findings here expand upon this simple questioning and further add to the understanding that probability cueing under this context tends to operate below conscious level.

In sum, this experiment established probability cueing in a visual search task. In the two stimulation groups, there was a general difference in search efficiency. The ARPC group showed improved RT compared to the CRPC group. However, this was not significant to the Sham group, so the directional effects of the two stimulatory groups cannot be disambiguated. The following experiment moves on from 2D search and instead investigated RPC tDCS effects on probability cueing and search efficiency in a 3D VE task. In this context, tDCS to the RPC may have a greater effect as the interaction with the environment and the task demands are more demanding than simple saccadic search (Smith et al., 2010). VE studies during fMRI have provided evidence to show that the RPC is active within this context supporting general spatial processing (Hampstead et al., 2014) and egocentric navigation and movement (Maguire et al., 1998 Riepe, Grön, Wunderlich, Spitzer, & Tomczak,

2000). Thus, Experiment 6 explored the role of the RPC during probability cueing within virtual space.

5.4 Experiment 6: RPC tDCS and virtual search

In Experiment 6, RPC involvement in probability cueing was tested using a VE task. The task was the same as that used in Experiment 4, insofar as participants were required to find a target in a VE, that, in the probability cueing trials, was spatially manipulated to appear more frequently on one side of space then the other. Unlike the visual search task used in Experiment 5, the virtual search task was 3D and maintained an egocentric viewpoint, meaning that as the participant interacted with the environment, the viewing angle consistently changed. As well as simplistic visual search tasks (e.g. Ball et al., 2013), fMRI (e.g. Hampstead et al., 2014) and TMS (Seemungal, Rizzo, Gresty, Rothwell, & Bronstein, 2008) studies have shown a key input from the RPC during virtual search tasks. For example, Hampstead et al. (2014) found that the superior parietal lobule (including the precuneus) was associated with spatial processing requirements whilst the intraparietal sulcus was associated with working memory and attentional task demands, during spatial learning in a VE. This example reiterates the assumption that a colliculur origin may not explain search and spatial learning under more immersive and realistic contextual constraints.

Although the same electrode montage was used in this experiment as Experiment 5, the design was, however, slightly different. Participants firstly completed a baseline block of trials - akin to the trials in the testing phase in Experiment 4. In these trials, the target appeared evenly. The addition of baseline

blocks meant that any initial biases in search profiles could be examined. For example, if the ARPC group were naturally biased towards the left (i.e. pseudoneglect) before the probability cueing trials began, this could interact with performance during the virtual search task. Baseline trials are therefore an effective way to measure individual differences in search performance and compare 'no learning' with 'learning' within each group. Other probability cueing studies, including the seminal study by Geng and Berhmann (2002), have adopted this approach (e.g. Jiang & Swallow, 2013, Jiang et al., 2016). In the present, it was predicted that all participants would perform the same during baseline trials, across all measures of spatial learning (search time, density, first visits, number of visits), and that although slight pseudoneglect was found in Experiment 5, search across space would be evenly distributed.

After undergoing either active or sham stimulation, participants completed probability cueing trials in which the target was spatially manipulated. Hence in this experiment, only the offline effects of tDCS were studied. For RPC stimulation, studies have shown varying lengths of after-effects, from 25 minutes (Ball et al., 2013) to 90 minutes (Clark et al., 2012). In relation to Experiment 5, a significant difference between online and offline blocks of trials was also observed, suggesting that offline blocks incurred superior performance to online blocks[8]. This suggests that using an offline protocol should still produce effects.

[8] Although the progression of learning was not related to tDCS (i.e. there was no group x block interaction effect), the results still demonstrate that learning was prominent after stimulation, and was not abolished.

Although RPC effects have been observed post-stimulation, no experiments have directly compared online and offline protocols separately using the same task. For example, Ball et al. (2013) use the same mixed online and offline design as Experiment 5 to investigate tDCS effects on a conjunction search task. This makes it difficult to disentangle practice effects and tDCS effects, since practice effects in visual search are common and lead to a reduction in RT over time (Wolfe, Cave, & Franzel, 1989). On the other hand, there has been some research that has examined other brain areas that have separated online and offline protocols. Pirulli, Fertonani and Miniussi (2013) found that anodal tDCS to the primary visual cortex had superior effects when a visual perceptual learning task was completed post-stimulation, compared to during stimulation. Martin, Liu, Alonzo, Green and Loo (2014) found the opposite, with online anodal tDCS to the dorsolateral prefrontal cortex resulting in improved skill acquisition on a cognitive training task, compared to offline stimulation. These studies highlight the intricate nature of tDCS, and demonstrate how its effect may be task, electrode and protocol dependent (Axelrod, Rees, Lavidor, & Bar, 2015). They also suggest that a pure offline approach may be a valid avenue to explore.

The same predictions were made for this experiment as Experiment 5 (see **Figure 5.2**). On a general level, it was hypothesised that measures of spatial learning post-stimulation would show polarity-specific effects with the ARPC group demonstrating enhanced probability cueing compared to the Sham and CRPC groups. At a specific level, it was predicted that tDCS would interact with the cued hemispace

with a stronger bias towards the cued side contralateral to stimulation (i.e. the left) after ARPC and a weakened contralateral bias after CRPC.

It is however, important to highlight that although some of the findings from Experiment 5 did not confirm these predictions, the environment under which probability cueing was examined in the present experiment are different. The VE task involves searching whilst the egocentric viewpoint rapidly changes as one interacts with the environment, whereas in visual search, the viewpoint is static. This also means that consistent spatial updating concerning position and rotation is required to effectively navigate, whilst spatial memory is necessary to remember previous visits and target locations. In a 2D, visual search environment, navigation is not necessary to complete the task and whilst spatial memory is used, its role is less prominent under this context compared to foraging-type searches (Gilchrist et al., 2001). Finally, it involves learning the cue in egocentric (i.e. viewpoint changes) and allocentric (i.e. stability of the cued side of the array, despite viewpoint changes) coordinates, whereas 2D search simply involves learning the distribution from a limited egocentric viewpoint (i.e. it is consistently defined by the viewers left or right). This again reiterates the assumption that the RPC may play a more prominent role in 3D search that entails greater task and cognitive demands. Although RPC tDCS effects have been demonstrated in more complex environments (e.g. Clark et al., 2012; Hampstead et al., 2014), this is the first experiment to directly investigate tDCS effects on search behaviour in a VE.

Although tDCS-induced hemispatial biases were not found in Experiment 5, hemispatial neglect patients have demonstrated deviant search patterns during VE

tasks, including: omitting targets within the left hemispace, preferentially starting search from the right side of space, undertaking sporadic search paths, slowing hand movements to control VEs and conducting greater revisits to previous target locations (Broeren et al., 2007; Buxbaum et al., 2006). Hence, CRPC tDCS, may replicate these search patterns in the current VE task. Presuming the effects of CRPC and ARPC tDCS are polarity-specific, it was predicted that ARPC would enhance efficiency to the left side of space.

After the experiment, all participants were questioned about their awareness of the probability cue (same questions and scoring as Experiment 3). It was predicted that there would no differences in awareness between the groups, and that, in line with previous VE experiments, learning would be below conscious level. Participants were also asked to clarify whether they believed they had received active or sham stimulation, but additionally they were also asked to rate their confidence. Furthermore, participants were also asked whether they had former experience with brain stimulation as it has previously been shown that participants who have experienced tDCS before are more likely to correctly identify their experimental group than naïve participants (Ambrus et al., 2012). This was therefore considered as measure of control and additional analysis was conducted to investigate whether this was the case in the pool of participants.

5.4.1 Method

5.4.1.1 Participants

Forty-four volunteers passed the tDCS Screening Questionnaire and took part in this experiment. However, one participant withdrew as they could not tolerate tDCS and another dataset was excluded as the participant fell asleep during the task. Therefore, in total, 42 datasets (24 female) were included in the final sample. 14 participants were randomly assigned to each experimental group: ARPC, CRPC or Sham. None of the participants met the exclusion criteria (**Section 5.2**).19 participants reported English as their first language. The age of participants ranged from 18 to 26 years (M = 22.37, SD = 2.08). All participants had normal to corrected normal vision, and as recorded by the EHI, 40 participants were right handed (M = 81.03, SD = 15.82) and two participants were left handed (M = -67.50, SD = 45.92). This was also confirmed by self-report. Participants received £9 for their participation.

5.4.1.2 Materials

The VE and desktop display used in this experiment was the same as Experiment 4. To recap, the environment consisted of four textured walls (brick and fence patterns), joined at the midpoint, with a grass texture applied to the ground. Start positions were at the north or south of the central midpoint. 12 red hemispherical items were positioned on the floor, representing the search items, and were positioned according to the combination that the participant was assigned to (see **Section 2.1.3**). Participants were required to 'walk over' the search item, using the arrow keys, until

they found a hidden 'target'. When the participant had successfully navigated over any item, a 'chime' sound played, providing audio feedback. The target was one of the 12 items and, when found, was indicated by a success message.

Participants firstly completed a baseline block. The baseline block consisted of 24 trials with the target located on the left 50% of the time, and on the right the other 50%. Each search item was sampled twice across the trial sequence. Trials were shown in a fully randomised order, so that target location repetitions were allowed. Repetitions in these trials occurred in 2.28% of trials (1008 trials completed across 42 participants).

After the baseline block and the tDCS period, participants completed two probability cueing blocks consisting of 30 trials per block (60 in total). The array did not change between baseline and probability blocks. The target was located 80% of the time on the cued side of space, and 20% of the uncued side. Per block, each search item was sampled four times on the cued side (creating 24 trials) and on the uncued side, each search item was sampled once (created 6 trials). The cued and uncued side of space (left or right) and the start positions (north or south) were counterbalanced across participants, although each VE combination was used across each experimental group. For example, one participant from Sham, ARPC and CRPC were exposed to combination one. Trials were shown in a completely random order, so that target location repetitions were permitted. The target repeated in 2.14% of trials (2520 trials completed across 42 participants). Participants were not told about the target likelihoods, nor that there was a difference in the targets location across the blocks. They were instructed to find the target as quickly as possible in all trials.

5.4.1.3 tDCS protocol

An offline stimulation approach was taken, whereby participants were tested on the two blocks of probability cueing trials after receiving 15 minutes of active or sham tDCS. Thus, any significant tDCS effects on probability cueing were attributed to post-stimulation (offline), after-effects.

5.4.1.4 Procedure

After being briefed on the procedure, participants were asked to sign a Consent Form and complete the tDCS Experiment Questionnaire. Once they were comfortable, the participant began a practice trial. Using the arrow keys on the computer keyboard, they were required to guide their movement over the search items, until the hidden target was found. A 'chime' sound provided the participant with feedback concerning whether their visit had been 'successfully registered' by the computer. If audio feedback was not heard, they were told to "reposition" and "walk over" the item again. Once the target had been found, a message appeared on the screen ("Target found!") and the trial automatically ended. The participant then began the 24 baseline trials. After each target was found, the participant pressed the space bar to initiate the proceeding trial.

tDCS was then set-up. The participant was informed when the tDCS was switched on and the ramp began, and was advised to sit comfortably during the next 15 minutes, during which time they received either active stimulation or sham stimulation. During the stimulation period, they watched a short extract from a movie.

After 15 minutes, the electrodes were removed and the probability cueing trials began. The participant was given the same instructions as before – to find the target as quickly as possible. 30 trials were completed, followed by a short break and another 30 trials.

Once the trials were complete, the participant was questioned the target likelihoods in the probability cueing blocks. Participants were questioned using the same method detailed in Experiment 3. The participant was then asked about their gaming hours and to complete: the tDCS Experiment Questionnaire, the EHI, the SBSODS and a general questionnaire concerning their current and previous experiences with brain stimulation and the Post-Experiment Checklist. The participant was then debriefed. The experiment took approximately 1 hour and 15 minutes.

5.4.2 Results

Spatial learning was measured using: search time, density, first visits and total number of visits. Each dependent variable was obtained using MazeAnalyzer, LabVIEW and Microsoft Excel, as detailed in **Section 2.1.3.4**. There was no pre-processing as participants received audio feedback concerning their accuracy of their visit to the search item.

Analysis was conducted for baseline and probability cueing blocks separately. For the baseline analysis, trials or locations were coded according to whether they were classified as cued or uncued later in the experiment. For example, search time for the baseline trials was classified according to whether the target was located on

the side that was cued or uncued in the probability cueing block. The probability cueing analysis for search time, first visits, density and the number of visits was conducted as per other experiments, with cued side as an addition.

Absent data

Some of the participants did not complete two blocks of probability cueing trials. This was due to timing issues, for example, some participants took longer than expected to complete the trials, or technical issues with tDCS, increasing the experiment time. In total, nine participants completed one block of probability cueing trials, meaning 33 completed two blocks. Of those who completed one block, three were assigned to the CRPC group and six were assigned to Sham. Thus, all ARPC participants (n = 14) completed two blocks of trials. So that a full dataset from all participants was analysed, data from those who completed Block 1, combined with Block 1 data from participants that completed the full experimental procedure was conducted (n = 42; ARPC: n = 14; CRPC: n = 14; Sham: n =14). Per group, six participants experienced the cue on the left side and eight participants[9] experienced in the cue on the right side.

Finally, as the questionnaires were computerised some data did not save. One tDCS before (CRPC participant) and two tDCS after ratings (1 Sham participant; 1 CRPC participant) did not save, as well as one EHI questionnaire (Sham participant).

[9] The counterbalancing was uneven as the aim was to recruit further participants, but this was not possible due to a lack of recruitment uptake.

5.4.2.1 Behavioural results

Search time

Median search times were firstly analysed in the baseline block using a mixed ANOVA with *trial type* (within-subjects factor; two levels: later cued, later uncued) and *group* as factors, to examine whether there were any initial biases in median search time across the groups. This ANOVA showed no significant difference between later cued (M = 18.24s, SD = 9.44) and later uncued trial types (M = 19.12s, SD = 7.41) ($F < 1, f = 0.08$). Furthermore, there was no significant difference in search time between the experimental groups ($F < 1, f = 0.15$; ARPC: M = 17.37s, SD = 7.64; CRPC: M = 19.05s, SD = 6.72; Sham: M = 19.62s, SD = 10.62). There was no significant interaction between the two factors ($F < 1, f = 0.21$).

A mixed ANOVA with *trial type* (within-subjects factor; two levels: cued, uncued), *cued side* and *group* was conducted on the probability cueing trials. There was a significant main effect of trial type ($F(1, 36) = 4.35$, $p = 0.047$, $f = 0.34$), demonstrating that search time was significantly quicker when the trial was cued (M = 13.52s, SD = 5.56) in contrast to when the trial was uncued (M = 17.50s, SD = 9.72). There was no significant main effect of group ($F(2, 36) = 1.55$, $p = 0.227$, $f = 0.29$; ARPC: M = 13.52s, SD = 5.88; CRPC: M = 16.44s, SD = 7.11; Sham: M = 16.61s, SD = 11.40). There was also no significant interaction between group and trial type ($F < 1, f = 0.19$).

There was no significant main effect of cued side ($F(1, 36) = 1.49, p = 0.230, f = 0.20$), indicating that search time was equal when the target appeared more

frequently on the left (M = 16.71s, SD = 7.51) and on the right (M = 14.63s, SD = 9.12) side of space. Furthermore, all interactions with the cued side were not significant: trial type and cued side ($F< 1, f = 0.10$), group and cued side ($F< 1, f = 0.14$) trial type, group and cued side ($F< 1, f = 0.18$).

First visits

For the baseline trials, first visits were coded as the percentage of trials in which the initial inspection was directed to locations that were classified as cued, in the probability cueing trials. A one-sample t-test showed that 49.40% (SD = 27.23) of first visits were directed to the later cued side of space; a percentage that was below 50% of chance ($t(41) = -0.14$, $p = 0.888$, $d = 0.02$). A one-way ANOVA also showed that there was no significant difference in first visits amongst the experimental groups: $F< 1$, $F< 1$; ARPC: M = 52.08%, SD = 32.51; CRPC: M = 50.00%, SD = 20.99; Sham: M = 46.13%, SD = 28.66.

First visits in the probability cueing trials was also entered in a one sample t-test, with 50% chance level, and a factorial ANOVA to examine any differences between the groups. First visits were not significantly above chance level ($t(41)$ = 1.48, p = 0.148, d = 0.23; M = 58.10%, SD = 35.55), suggesting that initial inspections were not directed to the cued side. Secondly, the groups did not perform significantly different from each other: $F< 1, f = 0.21$; ARPC: M = 57.86%, SD = 35.37; CRPC: M = 50.00%, SD = 37.21; Sham: M = 66.43%, SD = 34.73. The main effect of cued side was also not significant ($F< 1, f = 0.03$), suggesting that there was no difference in first visits when the cued side was on the left side (M = 59.08, SD =

32.94) or the right side (M = 57.36, SD = 38.08). There was no significant interaction between group and cued side ($F < 1, f = 0.23$).

Density

For the baseline trials, density was defined as the percentage of visits that were directed to locations that were later classified as cued. In these trials, density was not significantly above 50% chance level ($t(41) = 0.25$, $p = 0.803$, $d = 0.04$) indicating that search was even across both sides of space. Moreover, density across the groups was not significant ($F < 1$, $F < 1$): ARPC: $M = 50.88\%$, $SD = 19.47$; CRPC: $M = 50.84\%$, $SD = 8.0$; Sham: $M = 50.01\%$, $SD = 16.11$.

Density in the probability cueing trials was examined next. There were significantly more visits made to the cued side than chance level ($t(41) = 4.24$, $p < 0.001$, $d = 0.65$; $M = 62.95\%$, $SD = 19.80$). However, this effect was generalised across all the groups, as demonstrated by a factorial ANOVA ($F < 1, f = 0.05$; ARPC: $M = 65.20\%$, $SD = 21.44$; CRPC: $M = 56.10\%$, $SD = 17.24$; Sham: $M = 66.65\%$, $SD = 20.53$). The cued side also had no significant impact ($F < 1, f = 0.03$; left cued side: $M = 63.55\%$, $SD = 18.52$; right cued side: $M = 62.50\%$, $SD = 21.09$), and there was no significant interaction between cued side and group ($F < 1, f = 0.16$).

Number of visits

A mixed ANOVA with *trial type* and *group* was conducted on the number of visits baseline trials. This demonstrated no significant main effect of trial type ($F < 1$, $f = 0.14$; later cued: $M = 7.85$, $SD = 3.07$; later uncued: $M = 8.40$, $SD = 2.73$) or group

($F(2, 39) = 2.80, p = 0.073, f = 0.38$; ARPC: $M = 7.22$, $SD = 2.36$; CRPC: $M = 8.18$, $SD = 2.10$; Sham: $M = 8.98$, $SD = 3.83$), and no significant interaction between the two factors ($F < 1, f = 0.15$).

Secondly, the probability cueing trials for the number of visits was examined. A mixed ANOVA was conducted with *trial type*, *cued side* and *group* as factors. There was no significant difference between the number of visits made on cued ($M = 7.87$, $SD = 3.30$) and uncued trials ($M = 8.11$, $SD = 2.71$) ($F < 1$, $f = 0.05$). In comparison, there was a significant main effect of group ($F(2, 36) = 3.88, p = 0.030, f = 0.46$). Pairwise Comparisons (Bonferroni-corrected) showed that ARPC ($M = 6.94$, $SD = 2.18$) made significantly fewer visits than Sham ($M = 8.78$, $SD = 3.76$) ($p = 0.027$). There was, however, no significant difference between the number of visits made by CRPC ($M = 8.23$, $SD = 2.64$) and ARPC ($p = 0.186$) or CRPC and Sham ($p > 1.00$).

There was a significant interaction between group and trial type ($F(2, 36) = 6.45, p = 0.004, f = 0.60$). There was no significant difference between the number of visits made on cued ($M = 6.43$, $SD = 1.94$) and uncued trials ($M = 7.46$, $SD = 2.36$) when the participants received ARPC ($p = 0.370$). However, there was a significant difference when participants received CRPC stimulation ($p = 0.037$), with more visits made on uncued trials ($M = 9.46$, $SD = 2.76$) than cued trials ($M = 7.01$, $SD = 1.90$). There was also a significant difference between trial types for the Sham group ($p = 0.020$), although the relationship was reversed for this group, with more visits made on cued ($M = 10.16$, $SD = 4.27$) than uncued trials ($M = 7.40$, $SD = 2.65$). When the target was cued, there were significant effects between the groups ($p = 0.003$).

Pairwise Comparisons (Bonferroni-corrected) showed that there was a significant increase in the number of visits made by the Sham group (M = 10.16, SD = 4.27) in comparison to ARPC (M = 6.43, SD = 1.94) (p = 0.005) and CRPC groups (M = 7.01, SD = 1.90) (p = 0.021). There was no significant difference in the number of visits made by the ARPC and CRPC participants (p > 1.00). The effect of uncued trial types approached significance (p = 0.071). However, Pairwise Comparisons (Bonferroni-corrected) showed that no comparisons reached significance: ARPC (M = 7.46, SD = 2.36) and CRPC (M = 9.46, SD = 2.76) (p = 0.146); ARPC and Sham (M = 7.40, SD = 2.65) (p > 1.00); Sham and CRPC (p = 0.129). Overall, on cued trials, both stimulation groups made significantly fewer visits than Sham, of whom also made significantly more visits on cued trials than uncued trials. Further, CRPC made more visits when the trial was uncued, compared to cued. This interaction effect is in **Figure 5.7**.

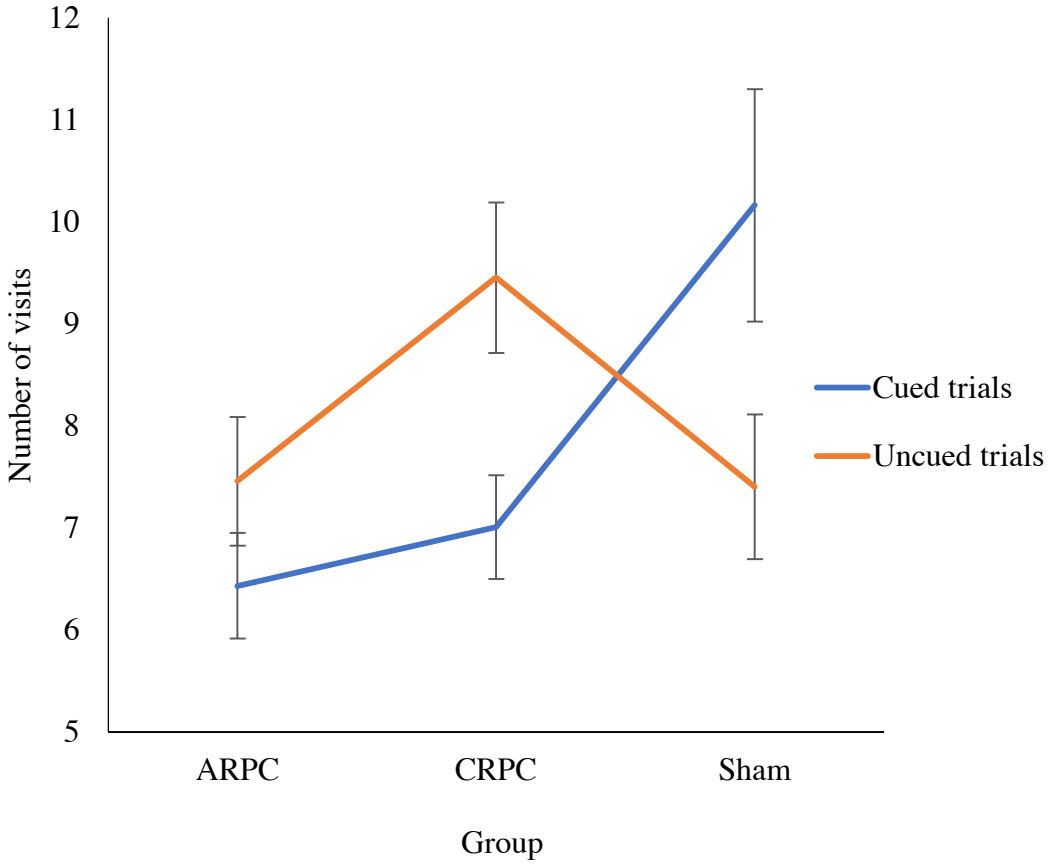


Figure 5.7 Significant group x trial type interaction effect. CRPC conducted significantly more visits on uncued trials than cued trials; Sham significantly increased their visits on cued trials than uncued trials, and conducted more visits on cued trials compared to ARPC and CRPC. Error bars represent +/- 1 standard error of the mean.

There was no significant main effect of cued side ($F < 1, f < 1$; left cued side: $M = 8.92$, $SD = 2.64$; right cued side: $M = 7.08$, $SD = 3.28$). There was, however, a significant interaction between trial type and cued side ($F(1, 36) = 9.77, p = 0.004, f = 0.52$). The effect of cued side at each level of trial type approached significance ($p = 0.074$). More visits were conducted when the cued side was on the left ($M = 8.92$, $SD = 2.18$) in contrast to the right ($M = 7.08$, $SD = 3.79$) on cued trials. When the trial type was uncued, the opposite effect was found; a greater number of visits were to the right side ($M = 8.94$, $SD = 2.40$) when the cue was on this side, in comparison to the

left side (M = 6.99, SD = 2.76) (p = 0.019). To reiterate, there was a cross-over difference: during cued trials where the target appeared most frequently on the left (uncued side on the right), more visits were made, whereas the opposite was found during uncued trials, with more visits when the cued side was on the right (uncued side on the left).

When the cued side was on the left, significance was approached (p = 0.068), with fewer visits on uncued trials (M = 6.99, SD = 2.76) than cued trials (M = 8.92, SD = 2.18). Alternatively, when the cued side was on the right, there was a significant difference, with more visits on uncued trials (M = 8.94, SD = 2.40) than cued trials (M = 7.08, SD = 3.79). This is in line with the previous cross-over effect: when the cued side was on the left, more visits were made when the trial type was cued, and instead when the cued side was on the right, more visits were made when the trial type was uncued.

Finally, there was no significant interaction between group and cued side ($F < 1$, f = 0.12) and no significant three-way interaction between group, trial type and cued side ($F < 1, f = 0.14$).

5.4.2.2 Individual differences

Post-Experiment Questions

88% of participants reported using a strategy to find the target (*binomial*, $p < 0.001$). When divided into separate groups, 86% ARPC, 93% CRPC and 86% Sham participants reported using a strategy. There was no significant association between

the groups and the use of a strategy to find the target (Fisher's Exact Test: $p > 1.00$, $V = 0.10$), suggesting that the stimulation type did not change reports of using a strategy.

When probed further and asked to explain their strategies, 31% of participants demonstrated some awareness of the probability cue. This was significant, in the direction of no reports of awareness ($p = 0.020$). Across the groups, CRPC reported the highest awareness of the probability cue (43%). 29% of ARPC participants reported awareness, followed by of 21% Sham participants. As before, there was no association between group and conscious awareness (Fisher's Exact Test: $p = 0.593$, $V = 0.20$). Overall, those who provided an explanation that indicated conscious awareness, on average, rated their confidence at 5.23 ($SD = 1.59$), in comparison to 5.55 ($SD = 1.33$) for those who did not express awareness of the cue. There was no significant difference between these ratings, when they were entered in an independent *t*-test with conscious awareness (aware vs. no awareness) as the grouping variable ($t(40) = -0.68$, $p = 0.499$, $d = 0.22$). The answers to Question 1 therefore suggest that although a large majority of participants did form a strategy, these demonstrated little conscious awareness of the probability cue.

For Question 2, participants were asked whether they had a sense of the target's likely location. Overall, 50% of participants reported that they did. This result was at chance level (*binomial*, $p > 1.00$). Across the separate groups, 57% of Sham participants reported having a sense, followed by 50% of ARPC and 43% of CRPC participants. A Chi-Square test showed that tDCS did not significantly modulate answers on this question ($\chi^2(2) = 0.57, p = 0.925$).

Following this, those who reported having a sense were asked to explain. 29% of participants provided answers that suggested that they had conscious knowledge of the cue. Like Question 1, this result was significant but in the direction of a lack of awareness (*binomial*, $p = 0.008$). This was also reflected when examining the groups individually. 7% of ARPC participants demonstrated an awareness. The CRPC group demonstrated substantially more awareness, with 43% of answers providing some explanation of the probability cue. 36% of the Sham group had awareness of the cue. There was no difference in responses across the groups (Fisher's Exact Test: $p = 0.097$, $V = 0.34$). Finally, when examining the confidence ratings, the mean ratings for the participants who expressed knowledge of the cue was 4.50 ($SD = 1.24$). The mean ratings for the participants who did not express knowledge of the cue was 4.93 ($SD = 1.44$). An independent *t*-test showed that there was no difference in these scores ($t(40) = -0.92$, $p = 0.366$, $d = 0.32$).

For the final question, 81% of participants accurately judged the cued side of space, and this result was above chance level (*binomial*, $p < 0.001$). 79% of participants in the active stimulation groups accurately identified the cued side. In comparison, 86% of Sham participants correctly judged the cued side. There was no significant association between the groups and correct judgement for this question (Fisher's Exact Test: $p > 1.00$, $V = 0.09$). When confidence ratings were examined, there was a significant difference ($t(40) = 2.98$, $p = 0.005$, $d = 1.12$) between those who correctly guessed the cued side ($M = 5.26$, $SD = 1.05$) and those who did not ($M = 4.00$, $SD = 1.20$), with correct judgements incurring significantly higher confidence ratings. An overview of the results is in **Table 5.4**.

Table 5.4 Experiment 6 - Post-Experiment Questions. Most participants guessed the cued side when presented with a forced-choice probe. $^{**}p \leq 0.001$ $^{*}p < 0.05$.

Question	Group	Answer	Result
1A - Strategy *"Did you use a strategy to search for the target in the environment"*	Total	Yes: 88% (n = 37) No: 12% (n = 5)	*Binomial:* $\mathbf{p < 0.001^{**}}$, in direction of more participant's reporting a strategy.
	ARPC	Yes: 86% (n = 12) No: 14% (n = 2)	*Fisher's Exact Test:* $p > 1.00$, $V = 0.10$, group was not associated with responses.
	CRPC	Yes: 93% (n = 13) No: 7% (n = 1)	
	Sham	Yes: 86% (n = 12) No: 14% (n = 2)	
1B - Strategy *"If YES please explain your strategy"*	Total	Awareness: 31% (n = 13) No awareness: 69% (n = 29)	*Binomial*: $\mathbf{p = 0.020^{*}}$, in the direction of no awareness of the probability cue.
	ARPC	Awareness: 29% (n = 4) No awareness: 71% (n = 10)	*Fisher's Exact Test:* $p = 0.593$, $V = 0.20$, group was not associated with responses.
	CRPC	Awareness: 43% (n = 6) No awareness: 57% (n = 8)	
	Sham	Awareness: 21% (n = 3) No awareness: 79% (n = 11)	
2A - Sense *"Did you have a sense of where the target was most likely to be in the environment?"*	Total	Yes: 50% (n = 21) No: 50% (n = 21)	*Binomial*: $p > 1.00$, less than 50% chance level.
	ARPC	Yes: 50% (n = 7) No: 50% (n = 7)	*Chi-square*: $\chi^2(2) = 0.57$ $p = 0.925$, $V = 0.34$, group was not associated with responses.
	CRPC	Yes: 43% (n = 6) No: 57% (n = 8)	

	Sham	Yes: 57% (*n* = 8) No: 43% (*n* = 6)	
2B – Sense "If YES please explain your 'sense' of the target's location"	Total	Awareness: 29% (*n* = 12) No awareness: 71% (*n* = 30)	*Binomial*: ***p* = 0.008***, in the direction of no awareness of the probability cue.
	ARPC	Awareness: 7% (*n* = 1) No awareness: 93% (*n* = 13)	*Fisher's Exact Test: p* = 0.097, *V* = 0.34, group was not associated with responses.
	CRPC	Awareness: 43% (*n* = 6) No awareness: 57% (*n* = 8)	
	Sham	Awareness: 36% (*n* = 5) No awareness: 64% (*n* = 9)	
3 - Final probe "If I told you that the target was more likely to appear on one side, would you be able to guess which one?"	Total	Correct judgement: 81% (*n* = 34) Incorrect judgement: 19% (*n* = 8)	*Binomial*: ***p* < 0.001**,** more participants correctly identified the cued side.
	ARPC	Correct judgement: 79% (*n* = 11) Incorrect judgment: 21% (*n* = 3)	*Fisher's Exact Test:* p > 1.00, *V* = 0.09. group was not associated with responses.
	CRPC	Correct judgement: 79% (*n* = 11) Incorrect judgement: 21% (*n* = 3)	
	Sham	Correct judgement: 86% (*n* = 12) Incorrect judgement: 14% (*n* = 2)	

Questionnaire Data

For the questionnaire analysis, cueing effects were calculated. The difference between search time and the number of visits on uncued and cued trials was calculated. For density and first visits, the raw percentage was entered.

Table 5.5 outlines the results from the correlational analysis. There were significant, positive relationships between the search time cueing effect and first visits (r= .70, p < 0.001) and density (r= .78, p < 0,001) cueing effects. Density was also positively related to first visits cueing effect (r= .92, p < 0.001). The number of visits cueing effect was, however, negatively correlated with search time (r= -.37, p = 0.016), suggesting that the difference between visits on uncued and cued trials became greater, the difference between search time on these trials became smaller. Although these cueing effect relationships were significant, there was no significant relationship between the number of visits cueing effect and first visits (r= -.16, p = 0.309) or density (r= -.16, p = 0.300) cueing effects. Cueing effects also did not significantly relate to any other questionnaire measures (p > 0.05).

In comparison, the confidence ratings from Question 1 of the Post-Experiment questions were positively related to the average gaming hours self-reported, per week (r= .38, p = 0.013). Question 2 confidence ratings were also significantly, positively related to Question 1 confidence ratings (r= .41, p = 0.007). Furthermore, gender was positively related to the SBSODS (r= .47, p = 0.002) and gaming hours (r= .35, p = 0.025). All other correlations were not significant (p > 0.05).

Table 5.5 Experiment 6 - Pearson's Product-Moment Correlations (r and α) and a Point-Biserial Correlation (r_{pb} and α) for the cueing effect and questionnaire measures, $*p < 0.05$, $**p \leq 0.001$

		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
1. Search cueing effect		-										
2. First visits cueing effect	*r*	**.70****	-									
	α	**< 0.001**										
3. Density cueing effect	*r*	**.78****	**.92****	-								
	α	**< 0.001**	**< 0.001**									
4. Number of visits cueing effect	*r*	**-.37***	-.16	-.16	-							
	α	**0.016**	0.309	0.300								
5. EHI	*r*	-.17	-.05	-.01	.04	-						
	α	0.284	0.765	0.932	0.803							
6. SBSODS	*r*	-.13	.01	-.02	.22	.04	-					
	α	0.398	0.942	0.922	0.159	0.816						
7. Gaming hours	*r*	-.09	-.07	0.001	-.09	.09	.06	-				
	α	0.553	0.657	0.994	0.581	0.592	0.717					
8. Question 1 – confidence ratings	*r*	-.03	.09	.05	-.24	.08	.07	**.38***				
	α	0.831	0.583	0.773	0.124	0.635	0.680	**0.013**				
9. Question 2 – confidence ratings	*r*	-.03	-.04	-.17	-.02	.02	.02	.08	**.41***	-		
	α	0.833	0.796	0.281	0.886	0.918	0.917	0.600	**0.007**			
10. Question 3 – confidence ratings	*r*	-.04	.05	-.04	.06	.12	.29	-.06	.11	.18		
	α	0.817	0.748	0.796	0.708	0.455	0.066	0.722	0.482	0.248		

11. Gender	r_{pb}	-.07	.11	.07	.03	.08	**.47***	**.35***	.27	.09	.02	-
	α	0.649	0.505	0.666	0.851	0.630	**0.002**	**0.025**	0.080	0.590	0.882	

Sham and active recognition

At the end of the experiment, participants were asked whether they thought they had received active or 'inactive' stimulation during the stimulation period. They were also asked to rate their answer on a 7-point confidence rating scale. Collectively, 57% of participants correctly guessed what condition they were in. However, a binomial test showed that this was not significantly above 50% chance level (p = 0.441).

There was a significant association between group membership and recognition scores ($\chi^2(2) = 7.58$, $p = 0.023$, $V = 0.43$). Post-hoc testing was conducted by examining the adjusted residuals[10] (Field, 2013; Sharpe, 2015). The adjusted residuals showed that significantly more Sham participants incorrectly guessed their stimulation condition, by claiming that they received active stimulation (adjusted residual = 2.60), in comparison to the other subgroups. 71% of participants within this group incorrectly believed that they had received active stimulation. This contributed towards the significant Chi-Square result. In comparison, adjusted residuals showed that significantly more ARPC participants correctly guessed that they had received active stimulation (adjusted residual = 2.00), in comparison to other subgroups. 79% ARPC correctly guessed their stimulation condition, suggesting that this figure significantly contributed towards the Chi-square statistic. The adjusted residuals for the CRPC group were 0.70, suggesting minimal contribution to the Chi-Square

[10] Adjusted residuals describe how much the cell contributed towards the overall Chi-square statistic and therefore how much this cell differed significantly from the overall total percentage. A value >1.96 represents a significant contribution and difference from the other cells. Positive and negative values describe the direction of the effect (Field, 2013; Sharpe, 2015).

statistic. 64% of participants correctly identified that they had received active stimulation in this group. The mean confidence ratings for the participants who correctly guessed their stimulation condition was 4.79 (SD = 1.38) whereas the mean confidence ratings for the participants who incorrectly guessed their stimulation was slightly lower (M = 3.78, SD = 1.40). These ratings significantly differed from each other ($t(40) = 2.34$, $p = 0.024$, $d = 0.73$), emphasising that accuracy was related to high confidence.

Former experience of brain stimulation

Participants were also asked whether they had experienced brain stimulation before. In total, 26.20% of participants reported experiencing brain stimulation before. This data was entered in a Chi-Square Test to examine whether participants who had received former brain stimulation were more likely to correctly guess their stimulation condition. There was, however, no significant association between former brain stimulation experience and correct recognition of experimental group (Fisher's Exact Test: $p = 0.299$, $V = 0.18$).

5.4.3 Discussion

Experiment 6 explored whether probability cueing in virtual space would be effected by RPC tDCS. Polarity-specific effects were predicted, with the assumption that CRPC would influence decrements in search efficiency whereas ARPC would enhance performance. In line with theories of right hemisphere attentional control (Bisley & Goldberg, 2010; Corbetta & Shulman, 2002; Heilman & Van Den Abell,

1980; Heilman & Valenstein, 1979; Kinsbourne, 1987), it was also predicted that ARPC would bias search more towards the contralateral side of stimulation (the left hemispace) whereas the CRPC would be inhibited towards this hemispace.

During baseline trials, there were no biases across all measures in search profiles. Later trials demonstrated probability cueing, although not across all measures. Search time was quicker during cued trials than uncued trials, and density was above chance level, demonstrating a systematic preference in visit rate towards the cued side. First visits, however, showed no such preference. A complex relationship between the number of visits and the cued side was found. When the cued side was on the left, more visits were made than when it was on the right, when the target appeared more frequently here. When the target was uncued, more visits were made when the cued side was on the right than when it was on the left.

Stimulation also influenced search performance. The CRPC group made a greater number of visits on uncued trials than cued trials, suggesting, against general predictions, a strong bias towards targets on the cued side of space. The Sham group committed more visits on cued trials than uncued trials, and this also differed from the number of visits on cued trials conducted by ARPC and CRPC. These stimulation groups committed significantly fewer visits than the Sham group when the trials were cued. No tDCS-induced hemifield biases were found. tDCS did not affect awareness of the probability cue, with minimal awareness of the cue. This finding is parallel to the other VE experiments reported in this Thesis, that suggest that probability cueing in virtual space operates below a conscious level.

The groups differed slightly in their sensitivity to probability cueing as demonstrated from the number of visits, with the CRPC group committing fewer visits on cued than uncued trials and the Sham group making significantly more visits on cued trials compared to ARPC and CRPC groups. As the active stimulation groups outperformed the Sham group on this measure, this may suggest the possibility that tDCS could protect against such inefficient strategies. This is not a polarity-specific prediction, however, as no significant differences were found between ARPC and CRPC.

This would not be the first study to demonstrate that ARPC and CRPC behave in the same way (e.g. Filmer, Mattingley, Marois, & Dux, 2013; Jones & Berryhill, 2012). Although much seminal research demonstrated polarity-specific effects, with anodal enhancing performance and cathodal weakening performance (e.g. Nitsche & Paulus, 2000), recent research has suggested that this may not be the case. A review by Jacobson et al. (2012) found that tDCS experiments examining cognitive functions tend to find effects more frequently with anodal than cathodal stimulation. Researchers have a 78% chance of finding anodal effects, compared to 48% of cathodal effects. Researchers also have a 16% chance of finding clear, polarity-specific effects with the two stimulation types, compared to when motor functions are investigated where researchers have a 67% chance of finding polarity-specific effects. Other cognitive studies have shown the unilateral effects of anodal and cathodal stimulation (e.g. Filmer et al., 2013; Jones & Berryhill, 2012). For example, Jones and Berryhill (2012) found that both stimulation types had an enhancing effect on a working memory task when the RPC was stimulation.

It is also important to bear in mind that the tDCS protocol in this experiment exploited an offline approach only. As described previously, there have only been a handful of studies to directly investigate the differences between online and offline stimulation (Axelrod et al., 2015; Martin et al., 2014; Pirulli et al., 2013) and these do not reach a consensus. During this experiment, and the previous and following experiment, current density was considered, to ensure that the reference electrode was below threshold for cortical modulation, whereas the active reference was above threshold (Nitsche et al., 2007). Studies that have examined the timing of tDCS on cognitive functions, all use densities that are above the advised threshold for the reference electrode. For example, Martin et al. (2014), of whom found superior online effects, used an electrode size of $100cm^2$ for the reference and a stimulation strength of 2mA – this provides a current density of $0.020mA/cm^2$ to this electrode. This could have influenced the effects that tDCS was having, including the current flow and direction. It may be that stronger current densities could influence greater behavioural effects (Nitsche et al., 2008), especially during an offline design where the neuromodulatory effects outlast stimulation abortion. Although this is speculative, it could be investigated but at a risk to participant safety (Brunoni et al., 2011). Computational modelling approaches, on the other hand, may be useful to understand the differences between online and offline stimulation without the need for experimentation.

Absent data was prominent in this experiment, meaning that some participants only completed one block of probability cueing trials after stimulation, rather than two blocks. One reason for this may have been that CRPC stimulation could induce a

general slowness of response, increasing the experiment length. This has been shown in other tDCS studies (e.g. Ball et al., 2013). Furthermore, neglect patients also show slowness of movement (i.e. bradykinesia), although this tends to be directional, with a pronounced effect to the left hemispace (Mattingley, Bradshaw, & Phillips, 1992; Mattingley, Husain, Rorden, Kennard, & Driver, 1998). Directional bradykinesia is also more pronounced in patients who have lesions to their RPC rather than frontal lobes, extending the importance of the RPC in spatial movement direction (Mattingley et al., 1998). Interestingly, all participants, no matter whether they had received Sham or CRPC, that completed one block of trials also experienced the cued side of the left side of space. However, the laterality of the cued side had no effect on either group, suggesting that the link between slower responses to the left hemispace under CRPC stimulation may be tenuous.

A final point of discussion for this experiment surrounds the addition of asking participants whether they had formally received brain stimulation or not. This question was added as previous research found that experienced tDCS subjects were more likely to accurately identify that they had received active stimulation, compared to naïve participants (Ambrus et al., 2012). However, the present experiment revealed no such relationship. Although this result diverges from the previous research, it may still be deemed relevant to ask as it could be a factor to consider if inefficient blinding occurs in the future. It adds an additional level of control.

In parallel to Experiment 1A, Experiment 6 established probability cueing in a VE. The effects of RPC stimulation were arguably greater in this experiment, compared to Experiment 5. Contrary to predictions and Experiment 5, both

stimulation types enhanced search efficiency, with the CRPC group committing fewer visits on cued trials and the ARPC and CRPC groups committing fewer overall visits compared to Sham. Overall, both anodal and cathodal RPC stimulation within a VE context modulated search, emphasising the potential role of this brain region.

To conclude all research in this Thesis, the final experiment again examines probability cueing under offline RPC tDCS conditions, in a laboratory environment, necessitating full-body search. This task builds upon the VE in complexity and task demands, requiring efficient navigation, full-body and head movement, energy expenditure and physical effort. Like VE search, the viewpoint and angle consistently changed, requiring effective updating of spatial attention and memory as the participant physically navigated through the 3D space. As discussed, a pure oculomotor account of probability cueing may not prevail when the task requirements and spatial processing are of increased intricacy. As the input of higher order processing may be more fundamental within a context requiring foraging-type searching, it was predicted that stimulation to the RPC would again modulate search efficiency and probability cueing to a greater extent than visual search.

5.5 Experiment 7: RPC tDCS and full-body search

In Experiment 7, probability cueing during a large-scale search task was examined. This search task was conducted using the same apparatus from the Smith et al. (2010) study and the basic tDCS parameters and protocol of the experiment was akin to Experiment 6. Participants were required to search an array of lights on the floor of room for a target light that was identified by a change in colour when it was

pressed. Baseline trials were firstly conducted, in which the target was evenly spread. This was then followed by an offline tDCS period[11], which used the same montage and dosages as the other experiments. Finally, participants completed two blocks of probability cueing trials, in which the target was spatially manipulated. The start position and search array were held constant throughout the trials, meaning that both egocentric and allocentric reference frames were aligned during the trials. The same measures as Experiment 6 were recorded: search time, first visits, density and the number of visits. Participants were then questioned about their awareness of the probability cue.

Smith et al. (2010) were one of the first researchers to suggest that probability cueing under such large-scale constraints may engage brain areas that process higher orders. This is in opposition to Geng and Berhmann (2002) who proposed that probability cueing works at an oculomotor level. Smith et al. (2010) suggested that the complicated nature of cueing under large-scale circumstances incites the use of high order processes, mainly due to the factors that the addition of full-body movements incur (e.g. alignment of reference frames, constant head and eye movement updating). Furthermore, efficient large-scale search involves greater, accurate decision making (Jiang et al., 2014; Smith et al., 2010) so that physical effort and energy is minimised, suggesting that a pure saccadic approach may not drive probability cueing within this context.

[11] Offline tDCS was also carried out in this experiment due to safety restraints i.e. the electrodes could slip during the task, putting participant safety at risk.

Although the RPC input in allocating attention within visual search is well-established (for reviews see: Colby & Goldberg, 1999; Sack, 2009), stimulating the RPC under large-scale search constraints may have the most pronounced effects due to the greater task demands. Furthermore, attentional deficits from hemispatial neglect carry over into daily life routines, suggesting that parietal lobe damage is detrimental within more realistic contexts.

The same predictions as Experiment 5 and Experiment 6 were made for this experiment (see **Figure 5.2**). On a general level, it was predicted that polarity-specific effects would be found, with ARPC stimulation improving and CRPC stimulation slowing probability cueing. Probability cueing would also be established in the Sham group. Although hemispace biases were not found in Experiments 5 and 6, for the present experiment, it was predicted that hemispace biases would occur, with the occurrence of polarity-specific effects towards the contralateral side of space to stimulation. This is because the RPC may have its strongest effects under this context. It was predicted that ARPC would be significantly faster at responding to the cue when it was on the left and the opposite was would be found for CRPC.

The same parameters that induced successful probability cueing in the original Smith et al. (2010) research were used in this experiment, namely an alignment of egocentric and allocentric reference frames (as described in Experiment 2 in their published research). By keeping the array (allocentric coordinate) and start position (egocentric coordinate) stable, they found that search was biased towards cued targets. These two factors were also held constant in Experiment 1A and Experiment 6 in the present Thesis, and similar probability cueing results were achieved in a VE.

However, unlike VE search and visual search, Smith et al. (2010) found that under full-body search, probability cueing was explicit in nature. This difference may potentially be because of the lack of physical movement required to complete VE and visual search, compared to laboratory search. For Experiment 7, participants were questioned about their awareness of probability cue. It was predicted that participants in this experiment *would* demonstrate an awareness of the cue, without the need for a forced-choice questioning. However, like Experiment 5 and 6, it was hypothesised that conscious knowledge of the cue would not be modulated by stimulation.

5.5.1 Method

5.5.1.1 Participants

Thirty-nine participants were recruited from the University of Bristol. Full data sets were, however, only obtained from 36 participants, due to technical faults with the large-scale apparatus. Therefore, the final data set included data from 36 participants only (19 females). 29 participants reported English as their first language. The age of participants ranged from 18 to 26 years (M = 21.14, SD = 2.02). All participants had normal to corrected-normal vision and were physically mobile. None met the exclusion criteria (**Section 5.2**). Participants were advised to tie all long hair back on the day of the experiment and wear non-restrictive clothing. According to the EHI and self-reports, 33 participants were right handed (M = 77.86, SD = 15.54) and used this dominant hand to complete the task. Two participants were left handed (M = -40.00, SD = 35.36), although one of these participants self-reported their handedness as ambidextrous, but used their left hand to complete the task. One other participant

was not strongly lateralised (EHI score: 0) but used their right hand to complete the task. Participants received £7 in exchange for their participation.

5.5.1.2 Materials

Search apparatus

The large-scale apparatus consisted of two rooms; an experimental space and an annex room where the Experimenter observed the participant. The two rooms were separated by a step and a curtain. The experimental space consisted of a 4mx4m grey carpeted space with a raised platform floor. Embedded in the floor was an array of 49 search locations, that were arranged in a concentric octagonal shape, consisting of one central light, an inner ring, middle ring and outer ring. In total, the side length of the structure was 1.14m, with 38cm between each light on the length. From the central light, to the light at the far edge of the shape, measured 1.5m, with 50cm between each light. The total area was 6.28m^2. A participant interacting with the environment is portrayed in **Figure 5.8**.

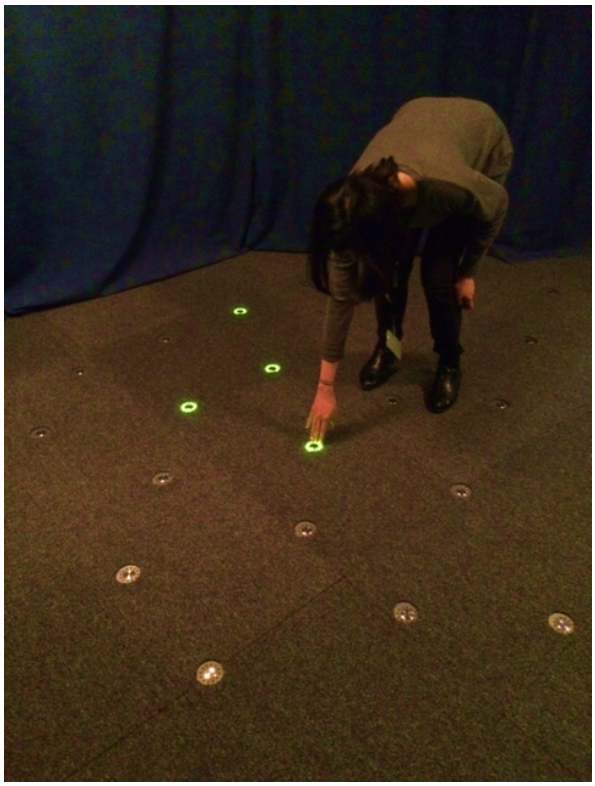


Figure 5.8 Participant interacting with the apparatus.

Each of the search locations (see **Figure 5.8**) were stainless steel circular switches that were 2.5cm in diameter. The switch was surrounded by an annulus of LEDs, measuring 6cm in diameter. These search locations allowed for the presentation of arrays of LEDs and for the measurement of search behaviour (to millisecond accuracy) to be recorded, as the participant interacted with the switches. Around the edge of the room was a curtain rail, which hung dark blue, featureless curtains. This concealed the walls and the entrance to the experimental space, which was found through the edge of two curtains that were securely fastened using Velcro. The large curtain did not have any obvious breaks in it, meaning all sides of the room looked identical. There were no obvious landmarks. The room was dimly lit, with both lights and ceiling being concealed by semi-opaque white material.

Throughout the whole experiment, the Experimenter was seated in the annex room which was next to entrance to the experimental space. This room contained two computers that controlled the search apparatus using Matlab 2009. A monitor displayed a live image from the experimental space using a closed-circuit television camera, of which participants were aware.

Search arrays

Any locations that were positioned along the sagittal midline, directly adjacent to the mid-section, or that were immediately within reaching distance of the participant from their starting position were not used to encourage the participant to move throughout the room during the trials. These illegal locations are demonstrated in **Figure 5.9** as white circles. There were 10 search locations illuminated (in green) on each trial, meaning that there were five search locations on the left and right sides. The array was not extinguished between trials, nor did the search locations extinguish once they had been activated within trials. A target was present on each trial but was not visually distinguishable without activation, which was indicated by a colour change from green to red once the search location had been pressed.

At the beginning of each trial, participants started at a predefined start position, indicated by the illumination of an orange light on the perimeter of the search area. The participant was instructed to stand behind the start position and press the orange light when it glowed – it then extinguished. Pressing the start position initiated the timer and recorded any light presses made by the participant after this. The participant was aware of this. The search location was reset when the target was

found, changing back to green, and the start position was then illuminated. The start position was fully counterbalanced across participants, so that for each array, one of four start positions was sampled. This ensured that the start position was not biased towards the left or right side across the participant sample. These lights were positioned at the far north or south of the environment, and to the left or right the right of the participant. The start position was fixed throughout the experiment, and along with the fixed array throughout the trials, the cued side was represented in consistent egocentric and allocentric coordinates.

A series of randomisations ensured that the arrays were: unsymmetrical across both sides, there were an even amount of lights deemed 'near' and 'far' from the participants start position, that four search locations appeared on the outer and middle ring, and that two locations appeared on the inner ring. Each participant experienced one array only, but across all participants three arrays were used (illustrated in **Figure 5.9**), with 12 participants experiencing each array. Four participants per experimental group experienced each array. This ensured that each array was sampled equally within the groups and across participants. Each participant experienced the same array in the baseline and the probability cueing trials.

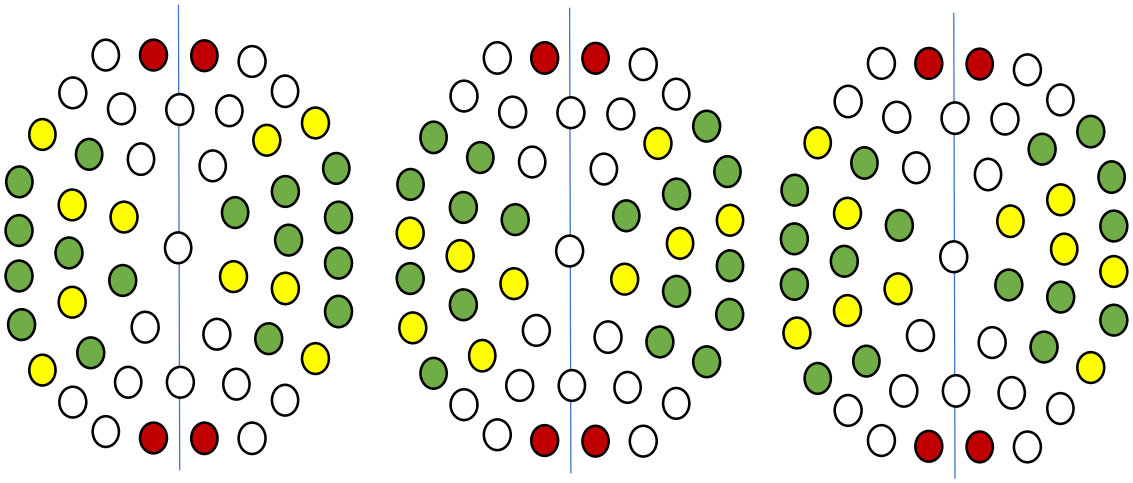


Figure 5.9 Experiment 7 arrays. Red indicates start positions; green indicates legal locations permitted during the array designs; yellow indicates potential target locations; white indicates illegal locations.

Trials

Participants firstly completed a baseline block, in which the target was located evenly (50%:50%) across the left and right side. The baseline block consisted of 20 trials. Each search location was sampled twice across the trial sequence and trials were shown in a fully randomised order.

After the baseline block and the tDCS period, participants completed two probability cueing blocks. Each block consisted of 25 trials (50 in total), with the target located 80% of the time on the cued side of space (20 trials per block; 40 trials in total), and 20% of the uncued side (five trials per block; 10 trials per block). For the cued side, each search item was sampled four times per block (eight in total) and for the uncued side each search item was sampled once per block (twice in total). The cued and uncued side of space (left or right) and the start positions (north-left, north-

right, south-left or south-right) were counterbalanced across participants. Trials were fully randomised, allowing for target repetitions. Participants were not told about the target likelihoods, nor told that there was a difference in the target's location across the blocks. They were simply instructed to find the target as quickly as possible in all blocks.

5.5.1.3 tDCS protocol

The same experimental groups (ARPC, CRPC, Sham), electrode montage (RPC/LPC), stimulation strength (1mA) and time (15 minutes/27 seconds for Sham) were used in this experiments as the others. As in Experiment 6, an offline stimulation approach was tested, whereby participants completed the baseline trials first, followed by a tDCS period, then the probability cueing trials.

5.5.1.4 Procedure

Each participant firstly signed a Consent Form and completed the tDCS Experiment Questionnaire. Following this, the participant was shown the apparatus and the search task was explained to them again. The participant was asked to hold a ball in their non-dominant hand so that they used their dominant hand only for the task.

Once the participant was stood behind the start position, the Experimenter exited the room. The Experimenter shouted 'Go!' from the annex, and the participant then pressed the start position when they were ready to go. This location then

extinguished and the participant was required to press, in any order, the search locations on the floor that were illuminated green. They were instructed to activate each of these locations until they discovered the one that illuminated red upon activation (i.e. the target) – all other locations remained green when activated. Once the target had displayed red, it reverted to green and the start location was illuminated. The participant was instructed to make their way back to it and to wait until the Experimenter said 'Go!' before beginning the next trial. Participants completed 20 baseline trials, in which the target appeared evenly across both sides of the room.

Following the baseline trials, the participant exited the room and the tDCS was set up. The electrode positions were measured and marked on the participants scalp and the tDCS was attached. Once the participant was comfortable, the tDCS was switched on, followed by 15 minutes of active stimulation, if the participant was assigned to ARPC or CRPC, or inactive stimulation after 27 seconds for Sham. During the preceding 15 minutes, participants watched a short extract from a film.

Following stimulation cessation, the participant was asked to go back into the experimental space and complete another set of "search trials". They completed 25 trials, with a break, followed by another 25 trials. In these trials, the target location likelihoods were manipulated.

After completing the trials, the participant was probed for their awareness about the probability cue. The same questions (strategy, sense of target's location and forced-choice probe) and scoring method used in Experiment 6 were also used in this

current experiment. For all questions, a confidence rating, on a 7-point scale, was made and scoring of conscious awareness was based on whether the explanations referred to the uneven target location or mentioned using the sides of the array to guide searches. Following this, the participants were asked to complete another copy of the tDCS experiment questionnaire, as well as the EHI, SBSODS, Post-Experiment Checklist and a general questionnaire concerning their past and present experiences with brain stimulation. The participant was then debriefed.

5.5.2 Results

Analysis was conducted in the same way as Experiment 6 (baseline and probability cueing trials separately). ANOVA's and *t*-tests were conducted on the data. Behavioural results

5.5.2.1 Behavioural results

Search time

For the baseline trials, a mixed ANOVA with *trial type* and *group* was conducted. There was no significant main effect of trial type ($F < 1$, $f = 0.11$) indicating that median search time was evenly spread across the two sides of space (later cued trials: $M = 7.43$s, $SD = 3.30$; later uncued trials: $M = 7.08$s, $SD = 3.50$). Search time also did not differ amongst the groups, as indicated by no significant main effect ($F < 1$, $f = 0.18$; ARPC: $M = 6.55$s, $SD = 3.50$; CRPC: $M = 7.67$s, $SD =$

3.63; Sham: $M = 7.55$s, $SD = 2.91$). There was also no significant interaction between these two factors ($F < 1, f = 0.16$).

A mixed ANOVA was conducted to investigate search time in the probability cueing trials. The factors entered in the model were: *block* (within-subjects factor; two levels: Block 1, Block 2), *trial type*, *cued side* and *group*. Search time was significantly faster on cued trials ($M = 6.05$s, $SD = 2.52$) compared to uncued trials ($M = 8.17$s, $SD = 3.48$) ($F(1, 30) = 11.96$, $p = 0.002$, $f = 0.63$). Search time did not, however, differ between Block 1 ($M = 6.98$s, $SD = 2.98$) and Block 2 ($M = 7.24$s, $SD = 3.44$) ($F < 1$, $f = 0.18$). On the other hand, there was a significant interaction between trial type and block ($F(1, 30) = 11.52$, $p = 0.002$, $f = 0.62$). The effect of block was significant within each level of trial type. For cued trials, search time was significantly faster in Block 2 ($M = 5.67$s, $SD = 2.55$) than Block 1 ($M = 6.43$s, $SD = 2.46$) ($p = 0.041$). For uncued trials, the opposite occurred; search time was significantly faster in Block 1 ($M = 7.53$s, $SD = 3.37$) than Block 2 ($M = 8.81$s, $SD = 3.52$). The effect of trial type within each level of block also showed that there was a significant increase in search time for uncued trials ($M = 8.81$s, $SD = 3.52$) in comparison to cued trials ($M = 5.67$s, $SD = 2.55$) ($p < 0.001$) in Block 2. However, there was no significant difference in search time in Block 1 for cued ($M = 6.43$s, $SD = 2.46$) and uncued trials ($M = 7.53$s, $SD = 3.37$) ($p = 0.110$).

There was no significant main effect of group ($F < 1, f = 0.18$) demonstrating that stimulation type (ARPC: $M = 6.64$s, $SD = 2.83$; CRPC: $M = 7.30$s, $SD = 3.62$; Sham: $M = 7.40$s, $SD = 3.15$) did not influence search time. There were no significant interactions between: trial type and group ($F < 1, f = 0.18$), block and group ($F(2, 30)$

= 1.19, p = 0.319, f = 0.28), and trial type, block and group (F(2, 30) = 1.20, p = 0.315, f = 0.28).

There was, however a significant main effect of cued side (F(1, 30) = 4.45, p = 0.043, f = 0.38) suggesting that search time was faster when the cued side was on the right (M = 6.40s, SD = 2.44) than the left (M = 7.83s, SD = 3.71). However the cued side did not interact with any factors, suggesting that stimulation did not bias search: cued side and block interaction: F< 1, f = 0.08; cued side and trial type: F< 1, f = 0.08; cued side and group: F< 1, f = 0.08; cued side, group and block: F< 1, f = 0.21; cued side, group and trial type: F(2, 30) = 1.95, p = 0.160, f = 0.36; cued side, block and trial type: F< 1, f = 0.05; cued side, block, trial type and group: F< 1, f = 0.22.

First visits

Firstly, a one-sample t-test was conducted on the baseline data to ascertain whether the percentage of first inspections were directed to the side of space that would later be cued. 53.75% (SD = 24.51) of first visits were directed towards this side, but this was not significantly above 50% chance level (t(35) = 0.92, p = 0.365, d = 0.15). There was also no significant difference between the percentage of first visits made to the later cued side by the ARPC (M = 61.25%, SD = 24.41), CRPC (M = 46.25%, SD = 7.81) or Sham groups (M = 53.75%, SD = 21.44) (F(2, 33) = 1.13, p = 0.334, f = 0.25).

Analysis of the probability cueing trials showed that first visits were significantly above 50% chance level in Block 2 (t(35) = 3.16, p = 0.003, d = 0.53; M

= 66.78%, *SD* = 31.90) but not Block 1 ($t(35) = 1.09$, $p = 0.283$, $d = 0.18$; *M* = 54.78%, *SD* = 26.27). This difference was confirmed when a mixed ANOVA was conducted with *block*, *cued side* and *group* as factors. There was a significant main effect of block ($F(1, 30) = 37.20$, $p < 0.001$, $f = 1.11$), with a significant increase in first visits in Block 2 (*M* = 66.78%, *SD* = 31.90) compared to Block 1 (*M* = 54.78%, *SD* = 26.27). There was no significant main effect of group ($F < 1$, $f = 0.06$), suggesting that the type of stimulation that participants received had no effect on the first visit direction (ARPC: *M* = 59.83%, *SD* = 29.41; CRPC: *M* = 62.00%, *SD* = 35.29; Sham: *M* = 60.50%, *SD* = 24.47). There was no interaction between the two factors ($F < 1, f = 0.10$).

There was no significant main effect of cued side (left cued side: *M* = 63.00%, *SD* = 30.06; right cued side: *M* = 58.56%, *SD* = 29.46; $F < 1, f = 0.06$). The interaction between group and cued side approached significance ($F(2, 30) = 2.20$, $p = 0.069$, $f = 0.44$). There were no significant differences between the groups when the target was cued to the left ($p = 0.198$) or the right side ($p = 0.303$) of space. Pairwise Comparisons (Bonferroni-corrected) also confirmed this. When the target was cued to the left side, there was no significant difference between the groups: ARPC (*M* = 54.00%, *SD* = 32.94) and CRPC (*M* = 79.67%, *SD* = 18.22) ($p = 0.333$); ARPC and Sham (*M* = 55.33%, *SD* = 27.67) ($p > 1.00$); CRPC and Sham ($p = 0.390$). Similarly, no significant effects were found when the target was cued to the right side: ARPC (*M* = 65.67%, *SD* = 24.15) and CRPC (*M* = 44.33%, *SD* = 38.35) ($p = 0.547$); ARPC and Sham (*M* = 65.67%, *SD* = 12.55) ($p > 1.00$); CRPC and Sham ($p = 0.547$). When examining the effects of the cued side within each level of group, there was a

significant effect. CRPC produced significantly more first visits to the cued side when this occurred on the left side ($p = 0.031$; $M = 79.67\%$, $SD = 18.22$) compared to the right side ($M = 44.33\%$, $SD = 38.35$). There was no difference between first visits made to the left or right side when it was cued for ARPC ($p = 0.461$; left cued side: $M = 54.00\%$, $SD = 32.94$; right cued side: $M = 65.67\%$, $SD = 24.15$) or Sham ($p = 0.513$; left side cued: $M = 55.33\%$, $SD = 27.67$; right side cued: $M = 65.67\%$, $SD = 12.55$). Therefore, the significant effect within CRPC, of more first visits directed to the left than the right side when this side was cued, was driving this near-significant interaction effect between group and cued side.

Finally, cued side did not significantly interact with block ($F < 1, f = 0.17$) and there was no significant three-way interaction between cued side, block and group ($F(2, 30) = 2.18, p = 0.131, f = 0.38$).

Density

Within the baseline trials, the percentage of visits made to the later cued side was 52.81% ($SD = 15.38$). Participants did not show a systematic preference for this hemispace ($t(35) = 1.11$, $p = 0.281$, $d = 0.18$). Furthermore, a one-way ANOVA demonstrated that there was no significant difference ($F(2, 33) = 1.55, p = 0.228, f = 0.31$) in density between the groups: ARPC: $M = 58.03\%$, $SD = 15.19$; CRPC: $M = 47.18\%$, $SD = 16.55$; Sham: $M = 53.21\%$, $SD = 13.54$.

For the probability cueing trials, two one sample *t*-tests were conducted to examine whether density was above 50% chance level. For Block 1, density was 64.11% ($SD = 15.87$) and this was significant ($t(35) = 5.33$, $p < 0.001$, $d = 0.89$). For

Block 2, there was an increase, with density at 71.91% (*SD* = 19.38) and this was also significant ($t(35) = 6.79$, $p < 0.001$, $d = 1.13$), demonstrating a systematic preference for the cued side across both blocks.

A mixed ANOVA was conducted to examine whether density differed across the blocks of trials, within the groups or between the egocentrically cued sides. This confirmed a significant main effect of block ($F(1, 30) = 11.56$, $p = 0.002$, $f = 0.62$), indicating that the percentage of visits significantly increased from Block 1 (*M* = 64.11%, *SD* = 15.87) to Block 2 (*M* = 71.91%, *SD* = 19.38). However, density did not significantly differ between the groups ($F < 1$, $f = 0.11$; ARPC: *M* = 66.51%, *SD* = 18.68; CRPC: *M* = 70.35% SD = 19.92; Sham: *M* = 67.16%, *SD* = 15.75) suggesting the difference was global. There was no interaction between block and group ($F < 1$, $f = 0.04$). There was no significant main effect of cued side ($F < 1$, $f = 0.04$), indicating that the cued side did not affect whether visits were directed to the left (*M* = 68.74%, *SD* = 19.31) or the right (*M* = 67.82%, *SD* = 16.88) side of space. Cued side also did not significantly interact with block ($F < 1$, $f = 0.04$) or group ($F(2, 30) = 2.51$, $p = 0.098$, $f = 0.41$) or both factors combined in a three-way interaction ($F < 1$, $f = 0.17$).

Number of visits

A mixed ANOVA with *trial type* and *group* was conducted on the baseline trials for the number of visits. This demonstrated no significant main effect of trial type ($F < 1$, $f = 0.17$) suggesting that the number of visits did not change as a function of trial type (later cued: *M* = 5.68, *SD* = 1.45; later uncued: *M* = 5.34, *SD* = 1.35). There was also no difference between the number of visits made in the baseline block

by ARPC (M = 5.55; SD = 1.59), CRPC (M = 5.50, SD = 1.46) and Sham participants (M = 5.60, SD = 1.22) ($F < 1, f = 0.07$). There was no significant interaction between group and trial type ($F < 1, f = 0.21$).

Additional analysis was conducted on the probability cueing trials. *Trial type, block, cued side* and *group* were entered in a mixed ANOVA. There was no significant difference in the number of visits made in Block 1 (M = 5.60, SD =1.49) and Block 2 (M = 5.63, SD = 1.91) ($F < 1, f = 0.04$). There was, however, a significant main effect of trial type, with a decrease in the number of visits made on cued trials (M = 4.96, SD = 1.43) compared to uncued trials (M = 6.27, SD = 1.72) ($F(1, 30) = 8.90$, $p = 0.006$, $f = 0.54$), and a significant interaction effect between trial type and block ($F(1, 30) = 12.92$, $p = 0.001$, $f = 0.64$). This is illustrated in **Figure 5.10**. Significantly more visits were made to cued trials in Block 1 (M = 5.29, SD = 1.31) than Block 2 (M = 4.64, SD = 1.48) ($p = 0.002$). The opposite was found for uncued trials, with significantly more visits in Block 2 (M = 6.62, SD = 1.78) than Block 1 (M = 5.92, SD = 1.60) ($p = 0.009$). For Block 1, there was no significant difference between the number of visits made on cued (M = 5.29, SD = 1.31) and uncued trials (M = 5.92, SD = 1.60) ($p = 0.169$). However, in Block 2, there was a significant difference between the number of visits, with significantly fewer visits made on cued trials (M = 4.64, SD = 1.48) compared to uncued trials (M = 6.62, SD = 1.78) ($p < 0.001$).

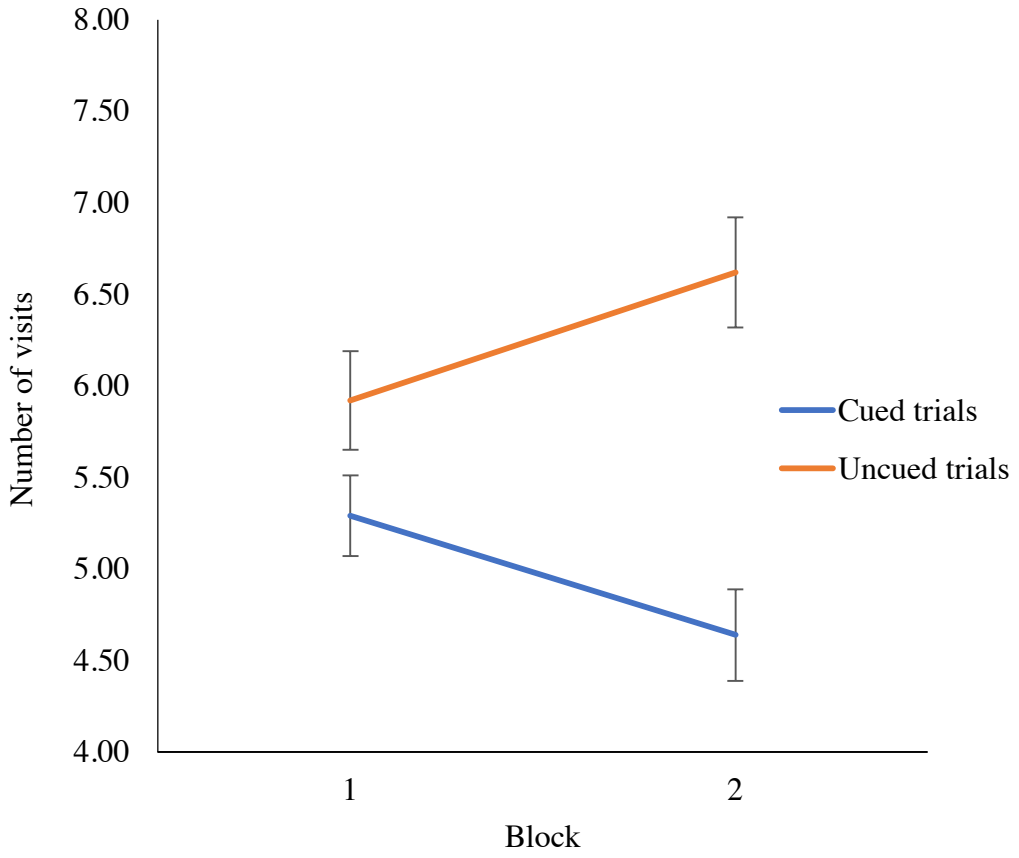


Figure 5.7 Significant trial type x block interaction effect. More visits were made on cued trials in Block 1 than Block 2, but uncued trials encompassed more visits in Block 2 than Block 1. In Block 2, there were fewer visits on cued than uncued trials. Error bars represent +/-1 standard error of the mean.

There was also no significant difference between the number of visits made by ARPC (M = 5.77, SD = 1.79), CRPC (M = 5.54, SD = 1.82) and Sham groups (M = 5.54, SD = 1.51) ($F(2, 30) = 1.68$, $p = 0.203$, $f = 0.34$). There was no significant interaction between trial type and group ($F < 1, f = 0.14$) or trial type, group and block ($F < 1$, $f = 0.11$). However, the interaction between block and group approached significance ($F(2, 30) = 2.77$, $p = 0.079$, $f = 0.43$). The overall effect of group within Block 1 was significant ($p = 0.022$). Pairwise Comparisons (Bonferroni-corrected) revealed that this significant effect was generated by a significant increase ($p = 0.020$)

in the number of visits made by ARPC participants (M = 5.95, SD = 1.67) compared to Sham participants (M = 5.33, SD = 1.06). CRPC (M = 5.53, SD = 1.64) and Sham participants did not significantly differ ($p > 1.00$), nor did the comparisons between ARPC and CRPC participants (p = 0.192). In Block 2, there were no significant differences between the groups (p = 0.667). Pairwise Comparisons (Bonferroni-corrected) also confirmed this: ARPC (M = 5.59, SD = 1.92) and CRPC (M = 5.55, SD = 2.02) ($p > 1.00$); ARPC and Sham (M = 5.76, SD = 1.86) ($p > 1.00$); CRPC and Sham ($p > 1.00$). The effect of Sham stimulation was marginal (p = 0.067). The number of visits increased in Block 2 (M = 5.76, SD = 1.86) compared to Block 1 (M = 5.33, SD = 1.06). There was no significant difference between the number of visits made in Block 1 and Block 2 for the participants who received CRPC (p = 0.957; Block 1: M = 5.53, SD = 1.64; Block 2: M = 5.55, SD = 2.02) and the participants who received ARPC (p = 0.130; Block 1: M = 5.95, SD = 1.67; Block 2: M = 5.59, SD = 1.92). Therefore, increases in the number of visits made by Sham participants from Block 1 to Block 2 and an overall increase between the number of visits made by ARPC compared to Sham in Block 1, account for the near-significant interaction between block and group.

The main effect of cued side approached significance ($F(1, 30) = 3.59$, p = 0.068, f = 0.35), suggesting that when the target was cued to the left side (M = 5.50, SD = 1.77) the number of visits were reduced in comparison to the right side (M = 5.73, SD = 1.64). There was a significant interaction effect between group and cued side ($F(2, 30) = 4.68$, p = 0.017, f = 0.56). When the target was cued to the left, there was no significant difference between any of the groups (p = 0.681). Pairwise

Comparisons (Bonferroni-corrected) also confirmed this: ARPC (M = 5.40, SD = 1.79) and CRPC (M = 5.53, SD = 1.92) ($p > 1.00$); ARPC and Sham (M = 5.58, SD = 1.67) ($p > 1.00$); CRPC and Sham ($p > 1.00$). When the target was cued to the right, there was a significant difference between the groups (p = 0.007). Pairwise Comparisons confirmed that the ARPC group (M = 6.13, SD = 1.75) made significantly more visits than the CRPC group (M = 5.55, SD = 1.76) and Sham (M = 5.50, SD = 1.38) when the cued side was on the right. There was no significant difference between the number of visits made by CRPC and Sham groups ($p > 1.00$). Within each group, ARPC participants also made significantly more visits when the target was cued to the right (M = 6.13, SD = 1.75) than the left (M = 5.40, SD = 1.79). However, there was no significant difference between the number of visits on left and right cued sides within CRPC (left side cued: M = 5.53, SD = 1.92; right side cued: M = 5.55, SD = 1.76; p = 0.951) and Sham participants (left side cued: M = 5.58, SD = 1.67; right side cued: 5 M = 5.50, SD = 1.38; p = 0.723). Thus, the ARPC group conducted more visits when the cued side on was the right, and fewer visits when the cued side was on the left, in comparison to both other experimental groups.

All other interaction effects in the ANOVA were not significant including: trial type and cued side ($F < 1, f = 0.08$), block and cued side ($F < 1, f = 0.06$), trial type, group and cued side ($F(2, 30) = 2.65, p = 0.087, f = 0.42$), block, group and cued side ($F < 1, f = 0.14$), trial type, block and cued side ($F < 1, f = 0.12$), and trial type, block, group and cued side ($F < 1, f = 0.04$).

5.5.2.2 Individual differences

Post-Experiment Questions

81% of participants reported using a strategy. A binomial test showed that this was above chance level ($p < 0.001$), indicating that most participants reported using a strategy to find the target. When examining the groups separately, 75% of ARPC participants reported using a strategy compared to 83% of CRPC participants. 83% of Sham participants also reported using a strategy. There was no significant association between the groups and responses (Fisher's Exact Test: $p > 1.00$, $V = 0.84$).

When participants were asked to explain their strategies, 53% acknowledged the target's likely location. This, however, was again not significantly above chance level (*binomial*, $p = 0.868$). 58% of ARPC, 50% of CRPC and, again, 50% of Sham participants demonstrated some awareness of the probability cue in their answers. There was no significant association between the groups ($\chi^2(2) > 1.00$, $V = 0.90$). Mean confidence ratings for the 'strategy' question were 4.92 ($SD = 1.32$). As demonstrated by an independent *t*-test, there was no significant difference in confidence ratings between those who expressed conscious awareness ($M = 5.22$, $SD = 1.27$) and those who did not ($M = 4.59$, $SD = 1.33$) ($t(34) = 1.44$, $p = 0.160$, $d = 0.48$).

Next, participants were asked if they had a sense of where the target was most likely to be. 64% of participants claimed that they did, although this percentage was not significantly above chance level (*binomial*, $p = 0.132$). 67% of ARPC and CRPC

participants reported having a sense, compared to 58% of Sham. The groups did not differ ($\chi^2(2) = 0.24, p = 0.887, V = 0.08$).

For the participants who reported having a sense of the target's likely location, they were asked to elaborate on this. 39% of answers demonstrated some awareness of where the target was in the laboratory space. Again though, this was not significantly above chance level (*binomial*, $p = 0.243$). Fisher's Exact Test ($p > 1.00$, $V = 0.80$) demonstrated no significant association between the stimulation type and the reports of awareness (ARPC: 42%; CRPC: 42%; Sham: 33%). Overall mean confidence ratings for this question were 4.36 ($SD = 1.55$). There was no significant difference in confidence ratings for those who did express conscious awareness ($M = 4.57$, $SD = 1.55$) and those who did not ($M = 4.23$, $SD = 1.38$) ($t(34) = 0.70$, $p = 0.492$, $d = 0.23$).

Finally, participants were required to make a forced-choice guess as to which side they believed the target was most likely to be situated. 97% of participants correctly guessed this side. This was significantly above chance level ($p < 0.001$). When divided into the separate experimental groups, 92% of ARPC, 100% of CRPC and 100% of Sham participants correctly guessed the cued side. Again, the groups did not significantly differ in their responses (Fisher's Exact Test: $p > 1.00$, $V = 0.24$). Overall mean confidence ratings were 5.67 ($SD = 1.26$), but responses could not be compared as only one participant incorrectly identified the cued side. An overview of the results is in **Table 5.6**.

Table 5.6 Experiment 7 - Post-Experiment Questions. All participants guessed the cued side correctly when presented with a forced-choice probe ** $p \leq 0.001$.

Question	Group	Answer	Result
1A - Strategy *"Did you use a strategy to search for the target in the environment"*	Total	Yes: 81% (n = 29) No: 12% (n = 7)	*Binomial:* $\mathbf{p < 0.001}$**, in direction of more participant's reporting a strategy.
	ARPC	Yes: 75% (n = 9) No: 25% (n = 3)	*Fisher's Exact Test:* $p > 1.00$, $V = 0.84$, group was not associated with responses.
	CRPC	Yes: 83% (n = 10) No: 17% (n = 2)	
	Sham	Yes: 83% (n = 10) No: 17% (n = 2)	
1B - Strategy *"If YES please explain your strategy"*	Total	Awareness: 53% (n = 19) No awareness: 47% (n = 17)	*Binomial*: $p = 0.868$, less than 50% chance level.
	ARPC	Awareness: 58% (n = 7) No awareness: 42% (n = 5)	*Chi-Square Test:* $\chi^2(2) > 1.00$, $V = 0.90$, group was not associated with responses.
	CRPC	Awareness: 50% (n = 6) No awareness: 50% (n = 6)	
	Sham	Awareness: 50% (n = 6) No awareness: 50% (n = 6)	
2A - Sense *"Did you have a sense of where the target was most likely to be in the environment?"*	Total	Yes: 64% (n = 21) No: 36% (n = 21)	*Binomial*: $p = 0.132$, less than 50% chance level.
	ARPC	Yes: 67% (n = 8) No: 33% (n = 4)	*Chi-square*: $\chi^2(2) = 0.24$, $p = 0.887$, $V = 0.08$, group was not associated with responses.
	CRPC	Yes: 67% (n = 8)	

		No: 33% (*n* = 4)	
	Sham	Yes: 58% (*n* = 7) No: 42% (*n* = 5)	
2B – Sense *"If YES please explain your 'sense' of the target's location"*	Total	Awareness: 39% (*n* = 14) No awareness: 61% (*n* = 22)	*Binomial*: *p* = 0.243, less than 50% chance level.
	ARPC	Awareness: 42% (*n* = 5) No awareness: 58% (*n* = 9)	*Fisher's Exact Test: p* > 1.00, *V* = 0.08, group was not associated with responses.
	CRPC	Awareness: 42% (*n* = 5) No awareness: 58% (*n* = 9)	
	Sham	Awareness: 33% (*n* = 4) No awareness: 67% (*n* = 8)	
3 - Final probe *"If I told you that the target was more likely to appear on one side, would you be able to guess which one?"*	Total	Correct judgement: 97% (*n* = 35) Incorrect judgement: 3% (*n* = 1)	*Binomial*: ***p* < 0.001**,** more participants correctly identified the cued side.
	ARPC	Correct judgement: 92% (*n* = 11) Incorrect judgment: 8% (*n* = 1)	*Fisher's Exact Test: p* > 1.00, *V* = 0.24. group was not associated with responses.
	CRPC	Correct judgement: 100% (*n* = 12) Incorrect judgement: -	
	Sham	Correct judgement: 100% (*n* = 12) Incorrect judgement: -	

Questionnaire Data

Cueing effects were calculated per measure in the same way as Experiment 1A (**Section 3.2.2**). **Table 5.7** outlines the results from the correlations between cueing effects and questionnaire data. There were significant, positive correlations between all the cueing effect measures, demonstrating that learning on one variable also incurred learning on another ($p < 0.001$). There was a significant positive relationship between Question 3 confidence ratings and search time cueing effect ($r = .40$, $p = 0.014$) and number of visits ($r = .34$, $p = 0.045$), indicating that enhanced learning incurred high confidence in guessing the target's likely whereabouts. First visits ($r = .31$, $p = 0.066$) and density ($r = .32$, $p = 0.055$) cueing effects approached a significant positive correlation with Question 3 confidence ratings. All other relationships did not reach significance ($p > 0.05$).

Table 5.7 Experiment 7 - Pearson's Product-Moment Correlations (r and α) and a Point-Biserial Correlation (r_{pb} and α) for the cueing effect and questionnaire measures, $*p < 0.05$, $**p \leq 0.001$

		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
1. Search cueing effect		-									
2. First visits cueing effect	*r*	**.83****	-								
	α	**< 0.001**									
3. Density cueing effect	*r*	**.89****	**.98****	**-**							
	α	**< 0.001**	**< 0.001**								
4. Number of visits cueing effect	*r*	**.90****	**.91****	**.96****	-						
	α	**< 0.001**	**< 0.001**	**< 0.001**							
5. EHI	*r*	-.06	-.22	-.19	.18	-					
	α	0.710	0.196	0.265	0.309						
6. SBSODS	*r*	-.23	-.07	-.14	-.16	-.29	-				
	α	0.171	0.702	0.421	0.350	0.082					
7. Question 1 – confidence ratings	*r*	.07	< 0.01	.07	.10	-.16	.17	-			
	α	0.695	0.994	0.674	0.549	0.345	0.320				
8. Question 2 – confidence ratings	*r*	.04	.08	.05	.03	-.10	.12	.24	-		
	α	0.822	0.651	0.765	0.869	0.569	0.474	0.154			
9. Question 3 – confidence ratings	*r*	**.40***	.31	.32	**.34***	-.24	-.02	.22	.19	-	
	α	**0.014**	0.066	0.055	**0.045**	0.156	0.922	0.191	0.257		
10. Gender	r_{pb}	-.01	-.07	-.02	.02	.16	.23	.15	.11	.16	-
	α	0.971	0.693	0.927	0.903	0.357	0.179	0.394	0.514	0.340	

Sham and active recognition

56% of participants correctly guessed which stimulation condition they had been exposed too. A binomial test showed that this was not significantly above chance level ($p = 0.618$). Upon examining each group separately, 58% of ARPC and Sham participants correctly guessed their group. 50% of CRPC participants correctly guessed that they had received active stimulation. A Chi-Square Test showed that there was no significant association between group membership and correctly guessing the stimulation type ($\chi^2(2) = 0.89, p > 1.00, V = 0.08$). The mean confidence rating for the participants who correctly guessed their stimulation type was 3.90 (SD = 1.55) whereas for the participants who incorrectly guessed, the mean confidence rating was 3.50 (SD = 1.51). There was no significant difference in these ratings ($t(34) = 0.78, p = 0.442, d = 0.26$).

Former experience of brain stimulation

Two Sham participants indicated that they had received previous brain stimulation (6%). There was no significant association between those who had received brain stimulation before and whether they correctly guessed their stimulation group (Fisher's Exact Test: $p = 0.492$, $V = 0.22$).

5.5.3 Discussion

Smith et al. (2010) investigated probability cueing within a laboratory space that required full-body movements to find the target. Probability cueing in this context was explicit and required a combination of egocentric and allocentric reference

frames. Experiment 7 attempted to replicate probability cueing under this context, as well as investigate whether RPC tDCS effected learning of the spatial cue.

There were no initial spatial biases detected in the baseline trials for any of the spatial learning measures. However, consistent with the expected learning effects, spatial biases were prominent in the probability cueing trials. On a general level, search time was faster when the target was in the cued hemispace, compared to the uncued hemispace, and this difference was greater in Block 2. Furthermore, a systematic preference for the cued side was demonstrated by a significant increase in the percentage of visits (density) made to this side as well as preference to direct first visits here in Block 2 compared to Block 1. The number of visits was also affected by the location of the target, with a decrease in the number of visits on cued trials compared to uncued, especially in Block 2. These results replicate those of Smith et al. (2010) in Experiment 2 of their study, as well as extend them by considering additional variables such as density and the number of visits. Probability cueing was therefore established in this large-scale search paradigm.

tDCS also had a general effect on the number of visits. Compared to Sham, ARPC participants increased the number of visits they made in Block 1. This could suggest additional exploration of the environment. Although this may seem like a logical strategy, it also highlights that the ARPC group were visiting more locations before finding the target, which could be interpreted as inefficient, especially as Sham did not show this effect. This result is opposite to the findings in Experiment 6, when ARPC committed fewer visits than Sham. Although ARPC may have been

detrimental to the number of visits in the present experiment, this result insinuates that the RPC may play a role in general search efficiency.

As suggested in Experiment 6, active stimulation may offer a protective effect to inefficient probability cueing. Compared to Experiment 5 and 6, at a more specific level, tDCS did produce some hemispatial biases which may suggest this. It was hypothesised that CRPC would demonstrate poorer search when the cued side was contralateral to stimulation (i.e. the left hemispace) and that ARPC would show an opposite enhancement. These polarity-specific effects were based on the understanding that anodal stimulation can enhance performance, whereas cathodal stimulation can inhibit it (Nitsche & Paulus, 2000; Nitsche et al., 2008), and that tDCS to the RPC has been shown to produce hemispace biases that are directionally-dependent upon the active stimulation administered (e.g. Sparing et al., 2009). In the case of Experiment 7, the effect of group approached significance when examining first visits, with CRPC directing a higher percentage of first visits to the cued side when it appeared on the left than the right. This suggests that after undergoing CRPC, search was biased towards the left, rather than inhibited towards this hemispace. ARPC mirrored these results when examining the number of visits made. The ARPC group made fewer visits, compared to CRPC and Sham groups, when the cued side was on the left, and this effect was also significant within ARPC, with fewer visits conducted when the cued side was on the left than the right. Thus, anodal and cathodal stimulation aided search when the target was more likely to appear within the contralateral hemifield. This result alongside the general search efficiency results (described above) suggest a greater need for RPC input during the large-scale,

foraging search, compared to 2D visual search (Experiment 5) and search in virtual space were full-body movement and navigational cues (Experiment 6) are absent.

One caveat of this experiment is that it is difficult to differentiate the level of dominance the RPC administrated in attention allocation as the LPC was not stimulated. In terms of models of attention (see **Figure 1.1**) based on hemispatial neglect, Heilman and collegues (1979; 1980) suggested that the right hemisphere dominates attention, by allocating it towards both hemispaces, whereas the left hemisphere purely controls the right hemispace. In comparison, Kinsbourne (1987) suggested that the two hemispheres reciprocate inhibition insofar as the left hemisphere controls the right hemispace and the right hemisphere controls the left hemispace. Thus, when one hemisphere is disrupted, attention is biased on the ipsilateral side.

Kinsbourne (1987) suggested that attention allocation was a result of reciprocal *inhibition*. Upon disruption, the damaged hemisphere becomes hyperactive, and the intact hemisphere instead becomes strongly inhibited. This over-activation results in an ipsilateral bias in attention and a contralateral neglect. Objects, for example, in the left hemispace are neglected and objects in the right are attended. The tDCS findings suggest an alternative explanation. Both stimulation types *enhanced* allocation to the *contralateral* side of space resulting in effective probability cueing when the target was on the left side, compared to when the target was *ipsilateral* to stimulation. This would instead suggest that under tDCS conditions, the 'inactive' (or intact) LPC stays strongly inhibited whilst the 'active' (or disrupted) RPC exhibits over-active behaviour that instead of resulting in a detrimental neglect effect,

demonstrated by an efficient shift of attention from the ipsilateral side of stimulation (i.e. the right) to the contralateral side of stimulation. tDCS to the RPC seems to not replicate the detrimental effects of left neglect but instead alleviates neglect to this side and strongly biases search towards it.

Instead, this result may be interpreted with Heilman and collegue's (1979; 1980) account that suggests that the RPC has a dominating role in attentional allocation. It controls both the left and the right sides of space and therefore an enhancing contralateral effect and disrupted ipsilateral effect could result from tDCS to the RPC. This framework seems more likely, but it is still difficult to tease apart the *exact* amount of control that the RPC has in probability cueing. To provide a clearer picture, the LPC could be actively stimulated. This has been considered before by Filmer and colleagues (2015). The authors administered offline anodal and cathodal tDCS (reference electrode on the central point) to the RPC and LPC to investigate its effects on accuracy to respond to targets presented on the right, left or bilaterally. They found that ARPC stimulation reduced detection to the left visual field and during bilateral presentations. This effect, however, was not found under ALPC conditions, suggesting a strong role for RPC and a minimal role for the LPC during stimulation detection to the hemispaces. They suggest that their results provide solid evidence for Heilman and collegue's (1979; 1980) account that predicts RPC dominance in attention allocation.

Behavioural effects aside, one striking finding was that participants expressed minimal awareness of the probability cue. This awareness did not differ with the stimulation type. Participants were only able to guess the cued side when presented

with a forced-choice probe, and their confidence ratings for this question were also found to positively correlate with all cueing effect measures, reiterating the understanding that high confidence incurs stronger accuracy and learning (Ais et al., 2016).

When using the same paradigm and design, Smith et al. (2010) instead found that probability cueing was explicit. However, other studies of large-scale probability cueing have demonstrated similar results to the one found in this experiment using different questioning techniques. In a series of probability cueing studies by Jiang and colleagues (Jiang & Won, 2015; Jiang et al., 2014; Won et al., 2015), participants were firstly asked whether they thought the target was equally likely to appear across four quadrants of the array. Participants had to answer 'yes' or 'no' and were not asked to elaborate. This question was then followed by a forced-choice question regarding identifying the cued quadrant. The authors argue that a high recognition rate for the last question (equivalent to Question 3 in the current experiment) suggests that explicit learning could be involved, but a lack of spontaneous recognition in the first question (equivalent to Question 1 and Question 2) suggests this is limited. The authors instead describe probability cueing as incidental learning, rather than a deliberate form of attention, not only because of its implicit nature but also the understanding that probability cueing reflects learning stable properties of the environment and is resilient to interference across time (Jiang et al., 2012; Jiang & Swallow, 2013). This interpretation makes sense across all the contexts tested in this Thesis, as well as within Experiment 7, as when probability cueing was present, it has consistently operated below conscious level. However, probability cueing may further

be understood by identifying a universally agreed way to gauge awareness across research, as this is variable.

In conclusion, probability cueing was established and replicated in a large-scale search paradigm. Unlike Experiment 2 reported by Smith et al. (2010), probability cueing appeared to operate below conscious level, resulting in a behavioural bias in search but little acknowledgement of this. The effects of offline tDCS to the RPC were also investigated. tDCS-induced general search efficiency disruptions and hemispace biases were found, reiterating that higher order brain areas may play a greater role under foraging-type search (Smith et al., 2010) as compared to saccadic search where the oculomotor region may be most accountable (Geng & Berhmann, 2002). ARPC and CRPC stimulation demonstrated an enhanced bias in search (according first visits and number of visits) towards the contralateral side of stimulation, suggesting that the attentional framework by Heilman and colleagues (1979; 1980) may be most appropriate to explain these results. This framework, alongside these tDCS results, would suggest that the RPC plays a role in attentional allocation, and that stimulation to this brain region can result in enhanced probability cueing effects to the contralateral, left side of space.

5.6 General discussion

Several studies have previously found that search behaviour can be prioritised to areas where a target most frequently appears (e.g. Geng & Behrmann, 2002, 2005; Jiang & Swallow, 2013; Kabata & Matsumoto, 2012; Smith et al., 2010). However, the neural systems that may work to support this strategy are currently unknown.

Experiments 5-7 investigated the potential role of the RPC in probability cueing under visual (2D search), 3D virtual and 3D, full-body search contexts. Probability cueing was established across the three forms of search, with a bias towards the hemispace that was cued (rather than uncued) in all experiments. For example, RT (Experiment 5) and search time (Experiment 6 and 7) was reduced when the target appeared on the cued side, compared to the uncued side. However, tDCS effects on probability cueing varied across the experiments. These results will now be discussed regarding their relation to the general and specific hypotheses.

The general hypotheses outlined the polarity-specific effects of tDCS was predicted to have on search behaviour. It was predicted that ARPC would increase neuronal firing rate (Nitsche & Paulus, 2000; Nitsche et al., 2008), inducing enhanced effects on probability cueing; CRPC was expected to show the opposite with a detrimental effect on probability cueing. It was also predicted that Sham participants would learn the cue, but this would be at a slower extent than ARPC and at a greater extent to CRPC. These predictions were derived from two types of evidence. Firstly, patients with lesions to the RPC that incur hemispatial neglect, show a probability cueing effect but to an attenuated magnitude (Geng & Behrmann, 2002; Shaqiri & Anderson, 2012). Secondly, research has demonstrated directional effects of enhancing anodal and impairing cathodal RPC tDCS (e.g. Sparing et al., 2009).

In line with general predictions, in Experiment 5, ARPC stimulation improved RT compared to CRPC stimulation, suggesting an enhanced effect for ARPC and an inhibitory effect for CRPC tDCS. This effect, however, was unrelated to probability cueing (i.e. no effect on cued or uncued trial types), indicating a general effect on RT.

Experiment 6 demonstrated that ARPC made fewer visits than Sham. These results indicate polarity-specific effects in the directions as predicted. However, some tDCS effects were not in these directions. In Experiment 6, it was also found that Sham made more visits than ARPC and CRPC when the trial was cued. CRPC also made a greater number of visits on uncued trials than cued trials, suggesting superior probability cueing. Experiment 7 also showed that ARPC made more visits than Sham in Block 1, and that Sham demonstrated an increase in the number of visits made in Block 2. Again though, these effects were not trial type specific and demonstrate general, overall differences between the groups rather than learning-specific effects.

These differences in findings demonstrate how polarity-specific tDCS effects are difficult to obtain and predict (Jacobson et al., 2012). Further, other studies that have stimulated the RPC also have not found clear effects. For example, Ball et al. (2013) found a general inhibitory RT effect with cathodal, but no effect of anodal stimulation. The results of Experiments 6 and 7 also demonstrate that tDCS did not affect all indices of search behaviour. In these experiments, probability cueing was examined using four dependent variables: search time, density, first visits and the number of visits. However, active stimulation effects were only found on the number of visits across both studies, and first visits for Experiment 7. This suggests that stimulation may have affected the way search was planned (i.e. where initial inspections were conducted) and the strategies undertaken across the trials (i.e. which locations search was directed too). Other studies have also found that tDCS can be very sensitive, such as Li et al. (2015) who found no tDCS effects on error rate during RPC/LPC dual stimulation on a number comparison and choice reaction time task, but

did find effects for RT. This adds to the complexity of the situation when attempting to design a tDCS experiment and highlights how sensitive and subtle these effects may be.

The specific hypotheses defined how the cued side of space would interact with hemispace biases induced by different stimulation types. Based on theories of hemispatial neglect (Heilman & Valenstein, 1979; Heilman & Van Den Abell, 1980; Kinsbourne, 1987) and the prediction that search would bias towards the cued side no matter what stimulation group, it was hypothesised that the ARPC group would demonstrate a strong enhancement of probability cueing when the cued side was on the left (contralateral to stimulation). The CRPC group would demonstrate the opposite, with a decrement to probability cueing when the cued side was on the left.

When probability cueing was examined in visual and VE search, no tDCS biases were introduced. Within a large-scale laboratory context, hemispace biases were discovered, although they were not as polarity-specific as predicted. CRPC participants directed more first visits towards the cued side when it was on the left than the right, indicating an enhanced search strategy. ARPC participants conducted fewer visits when the cued side was on the left than the right compared to CRPC and Sham groups, indicating a strong bias in search when it appeared on the side contralateral to stimulation. Hence, in this experiment, both stimulation groups demonstrated superior probability cueing when the cued side was in the left hemifield. The dominance of the RPC in the allocation of search may be at its greatest during foraging, full-body search when the distance travelled and the timescale is lengthy, especially compared to 2D visual search.

There are two possible reasons why tDCS hemispace biases were not expressed across all dependent measures and across the experiments reported here. Firstly, there are substantial differences in the stimuli presentation. tDCS experiments that have found hemispace biases tend to present single stimuli, either unilaterally or bilaterally, without any distractors present (e.g. Filmer et al., 2015; Roy et al., 2015; Sparing et al., 2009). This means that the tDCS effects of targets presented contralateral to stimulation, ipsilateral stimulation and across both hemispaces can also be studied in isolation. This also allows for Kinsbourne's (1987) theory of reciprocal activity to be explored more readily as a tDCS-induced imbalance would predict a mutual relationship whereby contralateral stimuli have attenuated or enhanced processing and ipsilateral stimuli demonstrate the opposite (Filmer et al., 2015; Roy et al., 2015; Sparing et al., 2009).

In the present experiments, although targets were not presented bilaterally, they were embedded within arrays (not presented in isolation) and their locations were probabilistically defined, meaning the sides of space always incurred a statistical disparity. In the case of Experiment 5, targets were hidden within an array of distractors. In Experiment 6 and 7, the scenes were far richer with additional context, including colour and 3D. To further this, the action outputs also gradually became more complex as the experiments progressed, from a singular button press, to greater manual effort, followed by physical effort and expenditure. It may be that the complexity of these environments deters some hemispace biases and weakens the overall effect. Equally, it may be that movement or the changes in viewing angle may interrupt tDCS effects. Perhaps tDCS effects are most prevailing when the

environment is fixed (such as 2D search) and that maintaining an allocentric representation of the cued side of space across different viewpoints cannot be disrupted by tDCS. Allocentric coding tends to be associated with the hippocampus, rather than the parietal lobes (Burgess, 2006) and as tDCS was not targeted here, this may explain why tDCS biases may be limited (see **Section 6.4** for further discussion on this). However, this explanation does not explain why hemispace biases were observed the greatest in an environment of the greatest complexity.

The second reason why hemispace biases were rare in these studies may be because of the electrode montage. In line bisection tasks (Benwell et al., 2015; Giglia et al., 2011) and target detection tasks (Medina et al., 2013), hemispace biases have been revealed by using a dual montage set-up. Like the set-up in the current experiments, one active electrode is placed on the RPC whilst the other is placed on LPC. However, both electrodes are the same size, meaning the same current density is emitted. These set-ups are predicted to modulate the inhibitory-excitability state of the underlying left and right hemispheres (Kinsbourne, 1987), causing adjustments in attention that replicate the hemispatial neglect effects. This type of set-up may have been effective for Experiments 5-7. However, this was avoided as it is extremely difficult to conclude which polarity to which hemisphere is having a prominent effect because the total current is the same for both hemispheres (Nitsche et al., 2008; Nitsche & Paulus, 2001).

Finally, across all experiments, probability cueing was probed using post-experiment questioning. It was predicted that the stimulation type would not affect the conscious awareness of learning. This is because hemispatial neglect patients also

demonstrate minimal knowledge of the cue during visual search, despite parietal lesions (Geng & Berhmann, 2002), and fMRI experiments have confirmed that damaged RPC areas are activated when targets are not consciously detected by these patients (Rees et al., 2002).

In line with visual search studies (e.g. Geng & Berhmann, 2002) in Experiment 5, probability cueing was found to operate below a conscious level: participants only identified the target when given a forced-choice probe. Equal to VE experiments reported in this Thesis, in Experiment 6, participants had little knowledge of the cued side. However, against predictions and previous research using the same large-scale search apparatus (Smith et al., 2010), participants in Experiment 7 were also found to demonstrate a lack of conscious awareness. tDCS was not related to conscious awareness in any experiments confirming that it did not modulate knowledge of probability cueing.

The finding that probability cueing operated below conscious level in Experiment 7 is surprising as the experimental parameters were the same as Experiment 2 of the Smith et al. (2010) study, in which awareness of the probability cueing was found to be explicit. The only differences in design between the two experiments was the number of search locations presented in the array (16 locations in Smith et al., 2010; 10 locations in Experiment 7) and the number of probability cueing trials tested (80 trials in Smith et al., 2010; 50 trials in Experiment 7). These design differences, especially the amount of trials completed, may have led to differences in awareness. It may be that explicit knowledge is formed with additional trials as this would incur longer exposures to the probability cue. However, other

large-scale experiments have demonstrated below conscious awareness with 192 trials, with search locations spanning across 64 possible locations (e.g. Jiang et al., 2014). Thus, these design variances seem unlikely to change the conscious nature of probability cueing, yet the reason behind the difference in awareness remains inconclusive.

Implicit learning is regularly cited in the probability cueing literature (e.g. Geng & Behrmann, 2002; Jiang & Swallow, 2013; Kabata & Matsumoto, 2012). It seems that within the contexts tested, there is no need for participants to explicitly track the statistical contingencies of the search display (Geng & Berhmann, 2002). This efficient search strategy requires attention to select and guide search towards the relevant target locations, yet the resulting learning is practically automatic, in that it appears to occur without intent or awareness (Jiang & Swallow, 2013; Turk-Browne et al., 2005). The assumption that learning eventually becomes automatised, as well as the finding that probability cueing seems to occur early on in a trial sequence (as demonstrated by differences in RT/search time to cued and uncued in the blocks in Experiment 7) could indicate the cued locations are consistently activating the attentional priority map within the RPC (Bisley & Goldberg, 2010; Corbetta & Shulman, 2002) and in turn biasing attentional weighting towards these areas. The search pattern that is likely to "win" the competition is one that has historically produced successful target localisation. There is no need to change strategy or to acknowledge the learning process because the initial decisions and weighting of attention towards cued areas consistently offers rewards (or has a higher probability of doing so).

Overall, the effects of RPC stimulation on probability cueing were investigated under various contexts. It was predicted that the RPC would be involved in probability cueing, based on tDCS studies that have exploited search paradigms (e.g. Ball et al., 2013; Roy et al., 2015; Sparing et al., 2009) and the models of attention based on patient with RPC damage (Bisley & Goldberg, 2010; Corbetta & Shulman, 2002; Heilman & Van Den Abell, 1980; Heilman & Valenstein, 1979; Kinsbourne, 1987). The tDCS experiments reported here demonstrate that probability cueing can be modulated by RPC stimulation, with changes in search induced by anodal and cathodal stimulation. The greatest tDCS effects were found in full-body, 3D search environments, suggesting that the RPC plays a more prominent role under this context compared to visual search, where instead an oculomotor account may suffice. This would seem logical as complex environments tend to incur greater physical and energy demands, meaning that the weighting of attention towards cued locations may be greater to reduce inefficient and costly expenditure.

6 Overview and general conclusion

Objects in the world are rarely randomly distributed (Biederman, 1972); instead they are statistically defined, occupying stable locations in the world. An example of this is looking for cutlery in a kitchen. Upon arriving at a holiday home and searching for cutlery, you might inspect locations where you believe the cutlery is most likely to be, such as in a drawer in a kitchen, rather than in the freezer. With minimal explicit knowledge, you prioritise these locations, and base this search on the previous experience in your own home. We are sensitive to these "statistical likelihoods". They are learnt incidentally and guide spatial attention (Jiang & Swallow, 2013), through consistent exposure to search locations that offer the most likely rewards. In turn, this saves time and physical and mental effort during the search process.

It has frequently been demonstrated that visual search can be biased towards areas of an array where a target is most likely to appear and that this bias operates below a conscious level (e.g. Geng & Behrmann, 2002, 2005; Jiang & Swallow, 2013; Kabata & Matsumoto, 2012; Stankevich & Geng, 2014; Walthew & Gilchrist, 2006). This effect has been coined 'probability cueing' (Geng & Berhmann, 2002). Researchers have suggested that it operates differently to other forms of attention (Jiang & Swallow 2013; Geng & Behrmann, 2005) as learning occurs rapidly over several hundred trials (Jiang & Swallow, 2013) and, unlike other forms of attention, the effects of it can last for weeks after training (Jiang et al., 2012) reflecting its persistence and resilience to interference. However, whether this probability cueing effect can be demonstrated across other contexts has rarely been explored. This is important to investigate as some

researchers (Klein & MacInnes, 1999; Thomas et al., 2006; Wolfe, 1994) have suggested that visual search behaviour is domain-general – in other words, the behaviour expressed under simple, laboratory-based visual search tasks is the same as real-world, full-body search. There is a strong assumption that statistical likelihoods aid real-world search but this has rarely been evidenced.

This Thesis examined probability cueing under a range of contexts and explored whether the RPC could be involved in the support of efficient learning. Each experiment will now be summarised, their practical and theoretical implications will be considered, and future research and conclusions will be discussed. The effect sizes for 'trial type' per measure, will also be compared across the experiments, as well as 'cued side' in the tDCS experiments. Effect sizes describe the magnitude of the differences found, whereas alpha values describe whether the differences are likely due to chance (Sullivan & Feinn, 2012). Hence, by evaluating these, the magnitude of spatial learning can be compared across the differing contexts and experiments.

6.1 Experiments 1 and 2: Probability cueing in virtual space

The initial experiments in this Thesis set out to examine probability cueing within a virtual search task. There were several reasons why this context was examined. Firstly, and as already mentioned, probability cueing is well-established but research tends to focus primarily on visual search. VEs are a medium between visual and real-world search, allowing for the behaviour to be explored in a way that is similar to real-world search (e.g. within a 3D environment with the maintenance of an egocentric viewpoint) but also under high levels of control. On the other hand, physical effort and

movement is reduced, like visual search. Thirdly, environmental set-ups like the ones used in these experiments (especially Experiment 2), are often used during industrial training (Moskaliuk, Bertram, & Cress, 2013), offering people a safe and risk-free environment to develop efficient behaviours that may be required for the completion of tasks that are difficult to train for under real-world constraints (Rose et al., 2000). Finally, the over-arching aim of these experiments was to use the VE to later examine whether probability cueing could be transferred from one context (VE) to another (laboratory space).

Experiment 1A explored probability cueing in a VE when the task was displayed on a monitor screen. In this task, participants completed 60 trials and on each trial, they were required to find a target that was hidden amongst 12 items presented on the floor of a VE. The target appeared more frequently on one side of the array (80%; cued side) than the other (20%; uncued side). It was predicted that participants would bias their search towards the cued side and that learning would be explicit – akin to laboratory-based probability cueing (Smith et al., 2010).

Probability cueing was established, as demonstrated by a reduction in search time across the trials and when the target was on the cued side, as compared to uncued side. A systematic preference for the cued side was also found, as a greater percentage of first visits and overall visits (density) were directed there, with an increasing preference as the trials continued. Finally, more visits were conducted when the target was positioned on the uncued side as compared to the cued side.

Experiment 1B also explored probability cueing under the same experimental context, but instead the trials were pseudorandomised so that within every 10 trials, eight cued locations were sampled and two uncued locations were sampled. This allowed for a finer grain analysis, with separate epochs of trials allowing learning to be tracked as the experiment progressed. However, under these circumstances, probability cueing was attenuated. There was no significant difference in search time or number of visits on cued or uncued trials across the epochs, and similarly, there was no systematic preference for first visits to be directed towards the cued side. The density of visits to the cued side, however, was above chancel level across all the epochs of trials.

Finally, in Experiment 2, the immersive properties of the task were enhanced and the VE was presented on a projected display. The task was adapted slightly to reduce simulator sickness, including: removal of textured walls replaced with solid colour walls, slowed rotational speed and reduction in the number of trials (30 trials, rather than 60 trials). The trial sequence was the same as Experiment 1A, so that a target appeared randomly rather constrained to epochs. As in Experiment 1B, probability cueing was not established across search time and the number of visits, although first visits and density demonstrated preferential search biases towards the cued side of space.

The effect sizes for 'trial type' are displayed for each measure within each experiment, in **Table 6.1**. A larger effect size (Cohen (1992, 1998): f = >0.40, d/d_z = >0.80) indicates stronger probability cueing. Although the main effect of search time was not significant in Experiment 1B, the effect size for it indicates that the difference between search time on cued and uncued trials was large. This could indicate that

participants were in fact biasing their search towards the cued side, reducing their search time when the target was most likely to appear here. On the contrary, across each experiment, first visits yielded small or medium effect sizes, even though, in the cases of Experiments 1A and 2, alpha values suggest significance. This indicates that, in total, first visits to the cued side of space may be trivial, as compared to other spatial learning measures that show parallel effect sizes that more accurately represent the corresponding alpha values. When significant, first visits may show the smallest of effects during probability cueing trials, potentially suggesting that participants do not necessarily plan which location to visit first.

Table 6.1 Effect sizes for Experiments 1A, 1B and 2 (*$p < 0.05$).

Experiment	Measure	Effect size	Definition
1A	Search time	**0.61***	f - Large
	First visits	**0.51***	d - Medium
		0.50*	d -Medium
	Density	**0.92***	d - Large
		0.97*	d - Large
	Number of visits	**0.65***	f - Large
1B	Search time	0.44	f - Large
	First visits	0.21	d - Small
		0.18	d - Small
		0.27	d - Small
		0.16	d - Small
		0.18	d - Small
		0.21	d - Medium
	Density	**0.78***	d - Large
		0.72*	d - Large
		0.53*	d - Large
		0.53*	d - Large
		0.49*	d - Medium
		0.60*	d - Large
	Number of visits	0.27	f - Medium
2	Search time	0.39	d_z - Small
	First visits	**0.61***	d - Medium
	Density	**0.83***	d - Large
	Number of visits	0.28	d_z - Small

Moreover, within each of these experiments, participants were probed for their awareness of the probability cue post-experiment. A relatively high number of participants reported using a strategy to find the target in Experiment 1A, but when probed further, their strategies did not reveal any knowledge of the likely target location. A small number of participants reported having a sense of the target's location,

but almost all could guess when presented with a forced-choice probe. These results were also reflected in Experiment 1B and 2, even though behavioural results demonstrated an attenuation of probability cueing.

Collectively, the behavioural results from these experiments suggest that probability cueing in a small-scale VE is possible, but only when trials are fully randomised (Experiment 1A). This could be because a randomised trial sequence incurs easier learning, as compared to a more structured trial sequence in which regular sampling of the uncued side of space could be detrimental to probability cueing, encouraging an evenly spread search. Moreover, the Post-Experiment Questions demonstrate that probability cueing operated below conscious awareness, equal to its operation during saccadic visual search (Geng & Berhmann, 2002). This may suggest that the removal of physical movement has a profound effect on the conscious level of probability cueing. However, it is important to highlight that the saccadic bias found in visual search is arguably far from the same bias found in virtual search, when the contexts, task demands and actions required to complete the task are not alike (Arthur et al., 1997; Waller et al., 1998). A potential way of testing whether physical effort is necessary for conscious awareness of the cue is to evaluate probability cueing under VE contexts that require full-body movement, such as HMDs or treadmills, which offer improved vestibular and multisensory information, compared to desktop environments (Ruddle & Lessels, 2009).

It is contradictory that in Experiments 1B and 2, participants to acknowledged the cued side when presented with a forced-choice probe, yet they did not bias their search towards the cued regions. This may have been because they had little intention

of using this information to guide their search (Jiang & Won, 2015). This lack of intention may link very closely to a lack of motivation. As discussed in **Section 3.3.3**, the reward for completing Experiment 1B was not monetary, and this may have influenced learning. Further to this point, in Experiment 2, several issues with the handling of the environment were highlighted, and in later experiments, adjustments were made to compensate for this. Some of these issues may have led participants to consistently miss the target, in turn, reducing their motivation to learn. Furthermore, simulator sickness in Experiment 2 was prevalent, and this has been shown to encourage low levels of attention and engagement with the task being tested (Maraj et al., 2017). Thus, defining probability cueing as pure 'incidental' learning (e.g. Jiang & Swallow, 2013) may not suffice. Probability cueing may be modulated by the motivational state of the participants during the trial sequence, in turn increasing their underlying intention to unconsciously learn the statistics of the environment.

A further way to investigate the unconscious function of probability cueing may be to measure presence during VE search. Presence is defined as the subjective experience of feeling as though the user is in one place (the VE) when they are physically within another (the laboratory space) (Witmer & Singer, 1998). Previous research suggested that highly immersive environments increased feelings of presence (Lin et al., 2002) allowing the adoption of more efficient cognitive strategies and the development of stronger memories for learnt items (Tan et al., 2006). It was predicted that in Experiment 2, participants would express explicit awareness of the probability cue, akin to the learning shown in full-body search (Smith et al., 2010). It was theorised that this may be due to the increased presence within this environment, encouraging the

participants to use strategies like those adopted under real-world environments. This was not found and, behaviourally, probability cueing was weak. Measuring presence across all VE search experiments may have ruled out the possibility that unsuccessful probability cueing was due to a lack of presence. Furthermore, it has been shown that higher feelings of presence, increase levels of motivation and engagement and decrease simulator sickness levels (Witmer & Singer, 1998), Measuring presence may therefore have also helped to disentangle the influence of motivation on probability cueing. Presence can be measured by physiological responses such as heart rate, skin conductance and skin temperature, with increases in all these measures related to subjective reports of presence (Riva, Davide, & Insko, 2003). Presence can also be measured using subjective questionnaire measures, such as the Witmer and Singer Questionnaire (Witmer & Singer, 1998) or the Slater-Usoh-Steed Questionnaire (Usoh, Catena, Arman, & Slater, 2000). This should be explored in the future.

These experiments highlighted the prevalence of simulator sickness rates. Five participants dropped out of these experiments: in Experiment 1A three participants withdrew and two participants withdrew from Experiment 1B. Experiment 2 was the only experiment in which simulator sickness was measured using the SSQ (Kennedy et al., 1993). Comparing SSQ ratings across experiments may have been valuable to deciphering the trade-offs between technology usage and its utility, as well as its potentially detrimental interaction with probability cueing.

Practically, these experiments (and especially Experiment 2, in which an immersive environment was used) highlighted some of trade-offs between technology and the utility of it, including mishandling of the controls for the environment and

simulator sickness. Learning in virtual space is especially important, as such immersive technology is used frequently, without the necessary evidence to demonstrate the effectiveness of it as a training tool (Rose et al., 2000). These experiments also suggest that minimal cost and low immersive environments (e.g. small-scale environments such as Experiment 1A) could be used rather than more expensive technologies (e.g. large projected screens such as Experiment 2). This is, however, tentative as the virtual space used in these experiments was very simplistic in nature and stripped of some of the cues that are used to aid navigation in the real-world (e.g. vestibular cues). VEs designed to reflect more realistic environments would need to be tested, such as real-world scenes where several rooms may be inspected during the trials.

Theoretically, these studies highlight the sensitive nature of probability cueing and that when attentional biases in search occur, they are powerful and evident across several dependent measures of spatial learning. Experiment 1A suggests that probability cueing may operate under a 'winner-takes-all' model (Bisley & Goldberg, 2010), with spatial attention actively biased towards regions of space that have been fruitful previously and are deemed behaviourally relevant. They also highlight that conclusions regarding the domain-generality of behaviour require more comprehensive scientific investigation. Further studies are necessary to examine behaviours under varying context, as well as an experimentation with different methodological factors (e.g. trial sequence).

6.2 Experiment 3: Probability cueing in full-body search

Experiment 3 examined probability cueing in full-body search. Probability cueing has only been studied in large-scale space in two experiments, although one of these experiments required the use of eye movements only to complete each trial (Jiang et al., 2014). Thus, the purpose of Experiment 3 was to replicate results of the probability cueing study conducted by Smith et al. (2010) by using a similar design, in which participants were required to actively search locations presented on the floor of an environment. Further to this point, this environment was also investigated as it was to later be used to examine the transfer of probability cueing between virtual space and laboratory space, thus the same spatial learning measures as before were recorded.

Participants were required to press LED lights on the floor, until one light illuminated, indicating that it was the target. Unbeknownst to participants, the target was cued to one side of the array. Probability cueing was not established in this experiment: search time was no quicker on cued, as compared to uncued trials, nor was there a decrease in the number of visits to the cued side of space. Although density was significant, suggesting a preference in visits to the cued side, first visits were no more likely than chance to be directed there. Post-Experiment Questions also reflected these results, and even when provided with a forced-choice probe, participants were unable to guess the cued side of space.

The findings from this experiment suggest that probability cueing was weak, with only density showing a significant effect. Effect sizes are listed in **Table 6.2**. The magnitude of the effects for each spatial learning measure are roughly reflective of the

alpha values, apart from search time. A medium effect size was found, yet no significant difference was established during analysis. As already mentioned, Post-Experiment Questions also reflected this lack of learning, unlike in Experiments 1B and 2 where participants expressed knowledge of the cue during forced-choice questioning, yet were unable to use this knowledge behaviourally.

Table 6.2 Effect sizes for Experiment 3 (*$p < 0.05$).

Measure	Effect size	Definition
Search time	0.35	d_z - Medium
First visits	0.06	d - <Small
Density	**0.69***	d - Medium
Number of visits	0.02	d_z - <Small

Although the design was based on a large-scale probability cueing study (Smith et al., 2010), there were several differences that could not be avoided. The shape differed and size of the environment was slightly smaller, which could have incurred restrictions on movement. Research has demonstrated that minimal movements can be detrimental to probability cueing (Jiang & Won, 2015), although this would not explain why probability cueing still occurs when movement is completely absent (i.e. in the case of visual search).

Compared to Smith et al. (2010), the number of search items and trials was also reduced, to be in line with the VE tasks. In total, participants completed 30 trials, and in the Smith et al. (2010) experiments, participants completed 80 trials. It could be that participants need further time and exposure to the cue when the search arrays are smaller. However, as discussed later in this chapter (**Section 6.4**), in another experiment

probability cueing was established using the same large-scale apparatus as the Smith et al. (2010) research, using a fewer number of trials.

Further research is necessary to explore how probability cueing operates under realistic constraints, to move research further into the domain of large-scale tasks. This experiment adds an additional layer to the current published data, but again, practically highlights how sensitive probability cueing can be, under carefully controlled experimental circumstances. The design of Experiment 3 was purposefully simple, and in line with Smith et al. (2010), was done so to create an environment that was reflective of visual search, whilst differing the action required to complete the task. However, real-world environments are full of landmarks that aid search processes (Vinson, 1999). Including a landmark that is not part of the search array but is assigned to the cued side may encourage probability cueing, by enabling participants to actively learn the cue and assign it to an allocentric anchor (Smith et al., 2010). In a VE context it has been shown that distinct landmarks can aid memory for locations (Tan et al., 2006) and rodent studies have also demonstrated that effective spatial learning is dependent upon stable landmarks (Jeffery, 1998). Furthermore, exploring large-scale search paradigms that are physically based within the real-world incur enhanced ecologically validity, allowing further research to deduce the powerful nature of efficient search processes.

6.3 Experiment 4: Transfer of probability cueing

Experiment 4 explored the transfer of probability cueing between a virtual and laboratory space. Participants were trained in the VE with probability cueing trials (akin to Experiment 1A) and were then exposed to a laboratory space where they completed

trials that had an even target distribution. The VE task was referred to as the training phase (80%:20% target distribution) and the laboratory space was referred to as the testing phase (50%:50% target distribution). The order of environments was tested in this way, as in Experiment 3, participants struggled to learn the probability cue under a laboratory set-up. The underlying reasoning for this experiment was that VEs tend to be used to train people to perform optimally, with the prediction that this behaviour effectively transfers to a real-world context (Moskaliuk & Cress, 2013; Waller et al., 1998). For example, pilots can be trained using simulated flight environments (Mazuryk & Gervautz, 1996). Despite this, it is generally *assumed* that trained behaviours transfer, with minimal exploration to examine if behaviours are truly transferred (Rose et al., 2000).

The assumption of behaviour transfer is also linked to researchers who consider visual search to be a domain-general mechanism (Klein & MacInnes, 1999; Thomas et al., 2006; Wolfe, 1994). This claim would suggest that behaviour transfer is swift and accessible across all environments as the mechanisms deployed in one is the same as another. A series of experiments by Jiang et al. (2016) examined the transfer of probability cueing across various visual search tasks, requiring saccadic movement and a single button press for trial completion. They found that task demands and qualities had an impact on the transfer of probability cueing.

Experiment 4 took this work further to investigate if probability cueing could be transferred between two tasks that required different actions to complete, namely hand movements via button presses in the VE and physical movement in the laboratory space. As the studies by Jiang et al. (2016) had suggested that the tasks should be

similar, several factors were held constant between the two environments, including the total search items and the arrays used. Thus, it was predicted that probability cueing would be learnt in the VE and effective transfer to the laboratory space would take place.

The results were analysed in the same way as Jiang et al. (2016): firstly, through an examination of probability cueing in the training phase, followed by an examination of consistent biases in search performance in the testing phase. Additionally, the first 10 trials per measure in the testing phase was analysed. In the training phase, probability cueing was not established. There was no difference between search time or the number of visits made on cued and uncued trials. Similarly, the percentage of first visits did not show a systematic preference to the cued side of space, however density did with a significant increase in the percentage of visits made to the cued side in Block 2, as compared to Block 1. In the testing phase, transfer was minimal. There was a significant difference with faster search time to uncued than cued trials as demonstrated within the first 10 trials, however this was in the wrong direction for optimal probability cueing. The number of visits was also significant, but again in the wrong direction, with more visits made when the trial was cued as compared to uncued. Although density was significant in the testing phase, this was no significant transfer to the training phase. First visits showed no significant effects in either phases.

Post-Experiment Questions also reflected a lack of transfer. In this experiment, participants were asked the same questions as before, but were asked about the VE and the laboratory space separately. For the VE, results were dissimilar to other experiments that found a lack of learning; participants were *not* able to correctly identify the cued

side of space when presented with a forced-choice probe and nor did any of their answers reveal conscious knowledge of the cue. For the laboratory space, the large majority of participants believed the target was spread evenly across the sides of space, suggesting a lack of transfer.

Effect sizes for this experiment were mixed (see **Table 6.3**). The only effect in the training phase to reach a large magnitude was density, in the second block of trials. This emphasises the lack of learning in this environment. These effect sizes also reemphasise the finding that participants expressed no knowledge of the cue in the Post-Experiment Questions for the VE – unlike in Experiment 1B and 2, where alpha values were not significant but effect sizes were sometimes large and probability cueing was expressed upon a forced-choice probe. The testing phase was also mixed, reflective of a lack of transfer, but the strength of the difference between the number of visits made on cued and uncued trials in first 10 trials was large. Although this effect size was large, the amount of cued and uncued trials the participant experienced in the first 10 trials varied greatly. Unlike in Experiment 1B, the trials were not separated into epochs, and were instead randomised. Thus, one participant could have experienced eight trials where the target was in a previously cued location, and another participant could have experienced eight trials where the target was in a previously uncued location. Although this finer analysis seems useful, a considerable caveat is that these comparisons and effect sizes regarding the first 10 trials, may be difficult to draw conclusions from.

Table 6.3 Effect sizes in Experiment 4 (*$p < 0.05$).

Phase	Measure	Effect size	Definition
Training	Search time	0.16	*f* - Small
	First visits	0.08	*d* - <Small
		0.22	*d* - Small
	Density	**0.55***	*d* - Medium
		0.74*	*d* - Large
	Number of visits	0.31	*f* - Medium
Testing	Search time	**0.78***	d_z - Medium
	First visits	0.35	*d* -Small
	Density	0.05	*d* -<Small
	Number of visits	**0.82***	*dz* - Large

Before discussing the theoretical reasoning for these results, it is important to highlight a practical, methodological difference between the VE task used in this experiment and Experiment 1A. Although the tasks were identical in their interactions and visual formats, sound was added into the VE to provide participants with feedback as to whether they had visited the search item. This was because in previous VE experiments, some participants missed the target and carried on searching, generating erroneous revisits to 'already searched' items. These revisits could have had a detrimental effect on probability cueing, especially in Experiment 2 where there was also a slight mismatch between the handling of the controls and the visual output from the environment. In a series of visual search studies, Mcdonnell, Mills, Mcculler, and Dodd (2014) found that telling participants to change their visual scan paths on each trial, eradicated the probability cueing effect, emphasising that a simple change in strategy can be detrimental. Furthermore, this research demonstrates that the learning of the probability cue may involve a degree of effort or motivation. In the case of

previous VE studies reported here, constant negative feedback could have been detrimental, meaning efficient strategies may have been purposefully changed to inefficient strategies; although this does not explain why probability cueing showed large effect sizes and significant results in Experiment 1A. In the case of the Experiment 4, there was less risk of this, although participants were instructed that if they did not receive the feedback, they should re-position and revisit the item until they heard the sound, to check for a potential target.

These points draw attention to the potential trade-off between utility and training technology in the modern, applied world. It may be costly for researchers and trainers to incorporate all the cues that are occur in the real-world, such as vestibular and rotational information, to allow for efficient transfer of behaviours. Moreover, this may require large spaces – which again, could be costly or difficult to gain with space or building constraints.

The trial order of the VE in Experiment 4 also differed from Experiment 1A. In Experiment 1A, the target did not repeat in the same location across multiple trials – thus intertrial repetition priming was reduced. In probability cueing tasks that have been conducted under visual search constraints, target location repetitions tend to be allowed (e.g. Geng & Behrmann, 2002), so to replicate this, repetitions were in Experiment 4 across both phases. During the testing phase, some participants did comment when the location was repeated, and potentially, before acknowledging this, they may have been performing inhibition of return in the training phase where probability cueing was taking place. Participants could have purposefully been avoiding previously visited locations. Inhibition of return is well-established in visual search (for a review see:

Wang & Klein, 2010) but has also been found to replicate in VEs (Thomas et al., 2006) and large-scale search tasks (Longstaffe, Hood, & Gilchrist, 2014). It is interesting that anecdotally, participants only commented on the repetitions during the testing, *not* the training phase. This may also reiterate the need for a stable landmark outside of the search array (e.g. differing textured floor patterns, separating the search array in half or in quarters) to aid probability cueing, orientation and navigation further in a VE context, if inhibition of return is being undertaken. Contrastingly, probability cueing was found to be significant when this task was replicated in a later experiment (Experiment 6 - discussed in **Section 6.4**). This instead suggests that, in Experiment 4, this methodological difference may not have been substantial enough to interfere with probability cueing.

Although probability cueing was not established in the training phase, this experiment still demonstrates the importance of examining the transfer of behaviour across various contexts. Density was the only measure in the training phase to show significant effects, with a greater percentage of visits directed to the cued side, than chance level, across both probability cueing blocks. However, this learning effect did not transfer to the testing phase in the laboratory environment, with no biases in visits found. It may be that moving rooms between the training and testing phase could be detrimental to cueing. It has been suggested that probability cueing may be viewpoint dependent (Jiang & Swallow, 2013) hence moving to a different room with a new viewpoint and into a new environment, could destroy any representations. However, if this was the case, further behaviours would need to be investigated, as in an applied context, training and testing phases are most likely to occur under very different

constraints and viewpoints (e.g. a virtual desktop world to a real-world battlefield). This result alone suggests that the transfer relationship may not be as clear-cut as expected, and that if behaviour will transfer requires scientific extensive investigation.

This experiment only examined probability cueing transfer between virtual and full-body search. Jiang et al. (2016) detail a set of experiments that have examined probability cueing transfer – although all the tasks tested required visual search only. Future experiments should explore the transfer of probability cueing across various other contexts, including visual search to real-world search or VE search to visual search, and vice versa. This will provide further understanding of the generalisation of visual search behaviour to foraging-type tasks (i.e. the dissociation of behaviour as domain-general vs. domain-specific).

Comparing transfer across multiple contexts will also allow for a more thorough picture of the theoretical reasoning behind probability cueing to be uncovered. Although researchers have suggested that visual search is a domain-general mechanism, collectively this study and the studies by Jiang et al. (2016) suggest that this assumption may not suffice and that attentional effects found in visual search may require further stable factors to reach significance under other contextual constraints. Furthermore, this also builds upon attentional priority mapping (Bisley & Goldberg, 2010) that predicts that locations that have previously provided rewards incur high attentional weight, as compared to those with low rewards. If visual search is a domain-general mechanism, the attentional weightings within the map would stay the same, no matter what context is under examination, meaning efficient transfer would consistently occur. In the case of the lack of transfer of density in Experiment 4, this

would alternatively suggest that when the environments vary greatly, and the action required to complete the task requires differing amounts of efforts, the attentional weighting of locations may take longer to adapt and 'tag' the relevant locations. Separating the testing phase trials into epochs (as in Experiment 1B), and examining the transfer of probability cueing across differing contexts, may offer further insight into the exact nature of attentional priority mapping adaptation via a finer analysis. Generalising a behaviour as either domain-specific or domain-general may be more complex than some researchers predict.

6.4 Experiments 5, 6 and 7: A role for the RPC in probability cueing

The neural mechanisms involved in probability cueing are largely unknown. Geng and Berhmann (2002) proposed that it functions at an oculomotor level, with saccadic eye movement primed (via superior colliculus activation) to the cued side of space. However, this does not explain how probability cueing can occur in large-scale space (Smith et al., 2010) in which task demands require higher decision making and further actions to complete such as full-body movement (Jiang et al., 2016). Instead, higher order brain regions may be involved, such as the RPC, which has been implicated in the control of directing and allocating attention across the two hemispaces (Bisley & Goldberg, 2010; Corbetta & Shulman, 2002; Heilman & Valenstein, 1979; Kinsbourne, 1987). This has been evidenced through a variety of neuroscience techniques, including non-invasive brain stimulation such as tDCS (e.g. Ball et al., 2013; Filmer et al., 2015; Giglia et al., 2011; Roy et al., 2015; Sparing et al., 2009).

Experiments 5-7, tested this theory by examining whether transcranial stimulation to the RPC disrupted or enhanced probability cueing. In Experiment 5, a visual search paradigm was used, in which participants were required to find a target letter within a simplistic search array during (online) and after (offline) tDCS. Experiment 6 instead used a virtual search task – the same task as Experiment 4 – to explore whether offline tDCS had an effect. Participants completed baseline trials (akin to the testing trials in Experiment 4), followed by stimulation, then two blocks of probability cueing trials (akin to the training trials in Experiment 4). Experiment 7 was conducted in the same format, but instead a laboratory search task was used. This task involved the same large-scale apparatus as used by Smith et al. (2010). The RPC was stimulated under all contexts using anodal (ARPC) and cathodal (CRPC) active currents and sham stimulation.

At a general level, it was predicted that probability cueing would be learnt in all experiments, but that ARPC would incur advancements to learning, whereas CRPC would incur decrements. Participants in the Sham condition would learn the cue, but at an intermediate level. This prediction was based on studies that have suggested that anodal stimulation can enhance performance, whereas cathodal stimulation can disadvantage performance (see Nitsche et al. (2008) for a review). Achieving stimulatory effects across all experiments may add to the debate as to whether probability cueing is a domain-general (i.e. same brain region involved across various contexts) or domain-specific behaviour (i.e. different brain region involved across various contexts). Behavioural results and effect sizes from this prediction will firstly be addressed.

Across all experiments probability cueing was mostly prominent. For example, in Experiment 5, RT was faster on cued trials than uncued trials, and in Experiment 6 and Experiment 7 the same pattern of results was found with search time. Density, first visits and the number of visits were additionally recorded in Experiments 6 and 7. There was no systematic preference to the cued side for first visits in Experiment 6, but in Experiment 7, this was significant in the second block of probability cueing trials. This pattern of results was repeated with significantly more visits made to the uncued side than the cued side in Experiment 7 only. The percentage of visits directed towards the cued side (density) did, however, show a significant preference in both experiments. In total, search time and density consistently demonstrated significant effects in both experiments.

In Experiment 5, participants in the ARPC group were faster to respond to all targets than participants in the CRPC group. This result was also in the direction of the hypothesis. In Experiment 6, CRPC participants conducted more visits when the trial was uncued, as compared to cued, which indicated stronger probability cueing in this group. ARPC participants also conducted fewer total visits than the Sham group and, together, the ARPC and CRPC groups conducted fewer visits than Sham participants when the trial was cued, indicating advanced probability cueing after undergoing both active stimulation types. Finally, in Experiment 7, the reverse effect was found, with ARPC participants demonstrating an increase in visits as compared to the Sham group in the first block of trials, and Sham participants increasing their total number of visits in the second block.

To summarise the results for the general hypotheses, across each of the tDCS experiments, the direction of stimulation was not always clear-cut or polarity-specific. Experiment 5 suggested enhancing effects of ARPC, whereas Experiment 6 suggested that both active stimulation types enhanced probability cueing. Sham participants performed poorly in the VE task, strongly below expectation. Experiment 7 found that the opposite of both experiments, with ARPC inducing slight decrements in performance as compared to Sham.

The effect sizes for this experiment (see **Table 6.4**) reveal a similar pattern of results to the alpha values. For example, at a universal level, RT and search time were consistently significant and yielded medium or large effect sizes, suggesting that search was biased and quicker when the target appeared on cued trials, across all experiments. For this spatial learning measure, probability cueing was strong and had an influence on the way that participants searched the spaces. However, and as already mentioned when summarising the results, probability cueing in Experiment 6 and 7 was variable, with the only consistencies in learning being density and search time – medium and large effect sizes were found for these significant measures.

Table 6.4 Trial type and group effect sizes for Experiments 5-7 (*$p < 0.05$).

Experiment	Measure	Factor	Effect size	Definition
5	RT	Trial type	**3.51***	f - Large
		Group	**0.32***	f - Medium
		Trial type x group	0.19	f - Small
6	Search time	Trial type	**0.34***	f - Medium
		Group	0.29	f - Medium
		Trial type x group	0.19	f - Small
	First visits	Trial type	0.23	d - Small
		Group	0.21	f - Small
	Density	Trial type	**0.65***	d - Medium
		Group	0.05	f - <Small
	Number of visits	Trial type	0.05	f - <Small
		Group	**0.46***	f - Large
		Trial type x group	**0.60***	f - Large
7	Search time	Trial type	**0.63***	f - Large
		Group	0.18	f - Small
		Trial type x group	0.18	f - Small
	Density	Trial type	**0.89***	d - Large
			1.13*	d - Large
		Group	0.11	f - Small
	First visits	Trial type	0.18	d - <Small
			0.53*	d - Medium
		Group	0.06	f - <Small
	Number of visits	Trial type	**0.54***	f - Large
		Group	0.34	f - Medium
		Trial type x group	0.14	f - Small

It is important to highlight across these experiments that tDCS did not interact with probability cueing per se. In some cases, the effects functioned at a global level, for example, ARPC participants were quicker to respond to targets as compared to CRPC participants in Experiment 5, indicating that the total RT was modulated *not* RT

to the cued or uncued side of space. If probability cueing was directly affected by tDCS, significant interactions between trial type and group, with large effect sizes, would be sought of. However, there was an absence of interactions, yielding small or below small effect sizes, for most measures across the experiments.

The global effects of tDCS on search efficiency were demonstrated by the significant main effects of group (or any interactions between group and other factors, such as block), with medium/large effect sizes. This was found for RT in Experiment 5 (medium effect size) and the number of visits in Experiment 6 (large effect size). This may suggest that tDCS influences general task efficiency rather than learning, parallel to other experiments where learning is absent but effects on RT or accuracy have been found (e.g. Ball et al., 2013; Sparing et al., 2009). However, this interpretation does not comply with other studies that have shown that tDCS can induce and disrupt learning effects (e.g. Clark et al., 2012). Furthermore, the general lack of significant results and large effect sizes for the 'group' variable suggest that the overall influence of tDCS on each of the tasks was not as strong, or as general, as expected.

These results also highlight how important it is to achieve sample sizes that are powerful enough to produce large effect sizes. For each experiment, the aim was to achieve 20 participants per tDCS group. This calculation was based on power calculations (see **Section 5.3.1**). For Experiment 6 and 7, this was not achieved and both experiments recruited below 20 participants per tDCS group. In fact, with a sample size of 42 in Experiment 6, the power to detect a large effect size for the factor 'group' drops down greatly to 0.73, as compared to a sample size of 60 which achieves a power of 0.87. Similarly, in Experiment 7, the power to detect a large effect size of 'group',

with 36 participants is 0.66. This would explain why the effect of tDCS at a group level, barely reached significance, but also emphasises the necessity for power calculations in research. On the other hand, with lower sample sizes, the interaction between group and trial type should still have surfaced, as for both experiments, the power to detect an effect with the achieved sample sizes was a lot higher (Experiment 6: 0.99; Experiment 7: 0.99). Thus, it seems although the between-subject effect of group was reduced, the sample size to detect any effect of tDCS on probability cueing (the main purpose of these experiments) was in fact valid with these reduced sample sizes. This reiterates that the lack of interactions between tDCS and probability cueing reported here are in fact valid.

Overall, the results here are varied. In general, tDCS may have a global effect on task efficiency, rather than probability cueing directly. These studies highlight the importance of examining several variables to provide a deeper picture of tDCS effects. In Experiment 5, the general hypothesis was partly met, with ARPC enhancing and CRPC disadvantaging RT. However, further experiments suggested that this polarity-specific prediction may not be directional, instead emphasising that these two stimulation groups may work in unison to enhance performance. This may be because in these two experiments, offline protocols were used, whereas in Experiment 5, a mixed protocol with offline and online stimulation was exploited. This was partly due to the practical limitations of tDCS when physical movement is necessary. However, although the underlying neural mechanisms of online/offline tDCS have been suggested (Stagg & Nitsche, 2011), the exact nature of how anodal and cathodal

stimulation interact during these protocols is unknown. This requires further examination.

At a specific level, these experiments hypothesised that contralateral hemifield biases would be observed, as these have been shown to occur during and after RPC stimulation in other cognitive tasks (e.g. Filmer et al., 2015; Giglia et al., 2011; Roy et al., 2015). Hemispatial neglect patients also demonstrate marked attentional deficits to the contralesional side of space, commonly after RPC lesions (Heilman & Valenstein, 1979; Husain & Rorden, 2003; Kinsbourne, 1987). It was predicted that ARPC stimulation would enhance cueing to the left side whereas CRPC stimulation would discourage cueing to this side. Results evidencing this hypothesis and effect sizes will now be discussed.

In Experiments 5 and 6, no tDCS-induced hemispace biases were found. Experiment 7 demonstrated some hemispace differences, with ARPC participants conducting fewer visits when the cue was on the left, as compared to the right, and compared to both CRPC and Sham participants. CRPC participants demonstrated a preferential first visit when the cue was on the left as compared to the right. This result counters the specific predictions, by instead suggesting that both stimulation types favoured the left side of space over the right.

To summarise the results from the specific hypotheses, under visual search constraints, tDCS did not induce any hemispace biases, suggesting RPC had little involvement in allocating attention within this context. This was also found when search was conducted in a representational, 3D space. However, when search involved

full-body movements, ARPC stimulation induced hemispatial biases by enhancing performance when the cue was on the left. However, against specific hypotheses, in the same context, CRPC tDCS enhanced performance to the left side too. The effect sizes of these results are detailed in **Table 6.5**. When hemispace biases were observed, the effect sizes were large, emphasising the magnitude of the effects. Equal to the results from the general hypotheses, these results also emphasise that tDCS tends to have a greater impact on hemispace biases when the testing environment is much more complex in nature. Further, under these types of environments, the predictive and polarity-specific nature of anodal and cathodal stimulation may not be so clear-cut, as demonstrated in Experiment 7 when the effects were unidirectional.

Table 6.5 Cued side and group effect sizes for Experiments 5-7 (*$p < 0.05$).

Experiment	Measure	Factor	Effect size	Definition
5	RT	Cued side	0.17	f - Small
		Cued side x group	0.11	f - Small
		Cue side x trial type	**0.34***	f - Medium
6	Search time	Cued side	0.20	f - Small
		Cued side x group	0.14	f - Small
		Cued side x trial type	0.10	f - Small
	First visits	Cued side	0.03	d - <Small
		Cued side x group	0.23	d - Small
	Density	Cued side	0.03	d - <Small
		Cued side x group	0.16	d - Small
	Number of visits	Cued side	<0.001	f - <Small
		Cued side x group	0.12	f - Small
		Cued side x trial type	**0.52***	f - Large
7	Search time	Cued side	**0.38***	f - Medium
		Cued side x group	0.08	f - <Small
		Cued side x trial type	0.08	f - <Small
	First visits	Cued side	0.06	d - <Small
		Cued side x group	**0.44***	d - Large
	Density	Cued side	0.04	d - <Small
		Cued side x group	0.11	d - <Small
	Number of visits	Cued side	0.35	f - Medium
		Cued side x group	**0.56***	f - Large
		Cued side x trial type	0.08	f - <Small

A common factor amongst these experiments was the prevalence of pseudoneglect. Other experiments in this Thesis found no such evidence of participants biasing their search towards the left side of space[1]. However, across Experiments 5-7,

[1] This was not reported in text, but further analysis demonstrated no effect of the cued side on any spatial learning measures, in Experiments 1-4

analysis of the cued side incurred very small effect sizes, indicating that differences in RT, search time, first visits, density and number of visits was of trivial magnitude. Apart from the number of visits in Experiment 6, the cued side and trial type interactions were also small or medium, again empathising the minimal effect that the egocentrically defined cued side had on probability cueing. This adds another layer to the probability cueing literature, confirming that general side biases in search are quite rare and have little effect on where the cued targets are most likely to be located within the array. Probability cueing can occur across both sides of space and does not favour one over the other, emphasising its effectiveness as an optimal search strategy.

Moving on from the behavioural results, across all experiments, probability cueing operated below conscious level. Participants were only able to identify the cued side upon presentation of a forced-choice probe. tDCS had no effect on conscious awareness. The results from Experiment 5 are parallel to the visual search literature, demonstrating that participants have a lack of conscious knowledge concerning the probabilities of search arrays (e.g. Geng & Berhmann, 2002). Experiment 6 demonstrates the same results as Experiment 1A, when probability cueing was at its strongest and found to also operate below conscious level. However, it is surprising that participants in Experiment 7 were unable to express knowledge of the cue, as experiments using the same large-scale apparatus have demonstrated that learning is explicit in nature (Smith et al., 2010). Other authors have instead interpreted that correctly guessing the cued side with a forced-choice probe suggests that participants may have partial knowledge of cue, rather than complete below conscious awareness

(Jiang & Won, 2015; Jiang et al., 2014; Won et al., 2015). This interpretation would hold for Experiment 7.

Moreover, it is difficult to explain why these results differ, but what is necessary is for researchers to identify a universal way of gauging awareness during probability cueing (Smith et al., 2010). Post-experiment questioning does not avoid the caveat of participants adapting their answers and inaccurately describing decisions as compared to those made during the experiment (Smith et al., 2010). Accurately gauging awareness is particularly difficult to achieve without the possibility of introducing experimenter bias or increasing participant curiosity leading to changes in strategies (Tunney & Shanks, 2003). Questioning could be conducted on a trial-by-trial basis; participants may be asked to identify how confident they are at predicting the target's location for the next trial. It has been shown that high confidence predicts accuracy (Ais et al., 2016) and when confidence ratings were required for Post-Experiment Questions, high confidence tended to correlate highly with stronger probability cueing effects (Experiments 4, 6 and 7). This type of awareness task may be useful, although again, this may lead participants to adapt their search strategies which could lead to detrimental effects on probability cueing (Mcdonnell et al., 2014). Alternatively, comparing the current questioning methods across differing tasks may allow researchers to examine whether results are reproducible.

Theoretically, these studies set out to examine the role of the RPC in probability cueing, as it has been suggested that the right hemisphere plays a role in the allocation of attention across space (Bisley & Goldberg, 2010; Corbetta & Shulman, 2002; Heilman & Valenstein, 1979; Kinsbourne, 1987). Kinsbourne (1987) suggested that, in

the intact brain, the right and left hemisphere work together, reciprocating inhibition, by allocating spatial attention to the contralateral hemifield. Heilman and colleagues (1979, 1980) instead suggested that the right hemisphere plays a more dominant role in spatial attention, guiding it across the hemispaces, whereas the left hemisphere allocates attention to the contralateral field only. Bisley and Goldberg (2010) and Corbetta and Shulman (2002) take these theories one step further and implicate the RPC in spatial attention. Together, these are evidenced from hemispatial neglect patients that demonstrate marked attentional deficits after a lesion to their RPC (Husain & Rorden, 2003).

It is difficult to conclude the precise dominance of the RPC in allocating spatial attention during probability cueing from these experiments. This is because the LPC was not stimulated, which would have enabled the precise roles of the two parietal lobes to be uncovered. What can be concluded though is that stimulation to the RPC did induce hemifield biases, especially within an environment with great task demands, and across each experiment, general attentional effects were also observed. The results from these experiments are in line with these attentional theories, implicating that the RPC may be involved in the efficiency of learning target likelihoods in search display, but its exact dominance requires further investigation.

Further to this point, it may be that the RPC is not the only brain region to be impactful during probability cueing. For example, during virtual and large-scale search, the hippocampus and the caudate nucleus may play a prominent role, as it has been shown that these brain regions aid the speed and accuracy of navigation and the memorability of spatial locations (Burgess, 2006; Maguire et al., 1997). Further,

egocentric and allocentric spatial coding may be due to slightly different neural correlates, with mainly parietal regions responsible for egocentric coding and hippocampal regions responsible for allocentric coding (Burgess, 2006; Gramann, Müller, Schönebeck, & Debus, 2006; Hampstead et al., 2014; Maguire et al., 1997). In Experiments 5 and 6, both reference frames were combined, meaning that both systems would have been necessary for coding the space accurately and supporting the learning of the cue. However, since tDCS can only affect the cortical surface, these areas are situated too deep in the brain for current to reach (Nitsche et al., 2008). This is a current practical flaw with tDCS. However, much recent studies have suggested that tDCS may work at a network level, with stimulatory effects influencing a wide range of brain regions (Callan et al., 2016; Hampstead et al., 2014). One study suggested that a parietal cathodal-frontal anodal electrode set-up increased activation and connectivity in the prefrontal cortices and posterior hippocampus during a virtual navigation task, as demonstrated using fMRI and tDCS combined (Hampstead et al., 2014). Using these two neuroscience techniques together could be a fruitful way to investigate the modulation of probability cueing in the future.

6.5 Overall evaluation and conclusions

Overall the experiments in this Thesis examined a well-established visual search behaviour and tested whether the same behaviour could be shown in much more complex environments. Probability cueing was established in virtual space but only when the trial order was randomised and when the environment was of minimal immersion (Experiment 1A and Experiment 6). Under these constraints, effect sizes

were also at their largest, emphasising that probability cueing was great in magnitude and that low-immersive environments, with the removal of full-body physical movement, may be useful to train efficient search strategies. Probability cueing was also established in large-scale laboratory search, replicating a previous research design (Experiment 7). It was also found to operate below conscious awareness. Overall, this suggests that although visual search behaviour may generalise to representational space, it is much more sensitive, requiring additional methodological and participant factors to be controlled. The exact essence of these factors requires further investigation, as well as the transfer of such behaviours across varying contexts. One may be to examine the motivational state of participants during learning under various contexts to build a more precise picture of whether probability cueing is purely 'incidental' (Jiang & Swallow, 2013) or whether a level of motivation or effort is required to learn the probability cue in environments that are much more multifaceted.

A general critique of probability cueing is the minimised power associated with comparing the cued and uncued trials. In all experiments (apart from Experiment 5) six uncued trials were compared to 24 cued trials per block. Arguably, this makes the data in these analyses unstable, because of the small number of samples within each of the measures (Kabata & Matsumoto, 2012). Although this caveat cannot be overcome, one further way to test probability cueing would be to see whether there is a threshold at which learning statistics becomes insignificant. Testing probabilities such as 60%:40%, rather than 80%:20%, may further divulge the statistical relationships between rewards (i.e. finding a target) and the biases that are prominent in search.

Another general consideration is to examine the search paths of participants, to see whether the strategies reported in the Post-Experiment Questions are similar to the way participants behaviourally search the environments. In visual search, this could be done with eye movement recordings. In virtual and laboratory search the paths that participants take could be mapped and classified. Analysing these could provide a more objective approach to classifying the strategies of participants, as well as enable the further validation of VE tasks by contrasting search strategies that are deployed in this context with real-world set-ups (e.g. Lessels & Ruddle, 2004). Analysis of search paths would also enable researchers to examine whether backtracking behaviour was taking place – an inefficient strategy that has been demonstrated before in VE tasks (e.g. Kaur et al., 1999). This type of strategy may also be indicative of a decrease in motivational state, so this may be a good way of discretely testing motivational levels. It may be that across these environments participants carry out similar search strategies, providing evidence for visual search as a domain-general mechanism. Furthermore, this would enable the examination of inhibition of return to the uncued side of space and whether the organisation, spatial layout and number of search items presented in the array may have an effect the way participants interact with and travel through the environments.

The neural mechanisms underlying probability cueing were also investigated using tDCS. These experiments suggested that the RPC may play a general role in task efficiency (such as enhancing search time) but more specifically, within larger-scale contexts, it may aid the learning of the spatial statistics of a search array, by directing attention towards the contralateral side of space when targets are more likely to appear there. On a practical level, these studies collectively demonstrate the effectiveness of

tDCS as a tool for enhancing search. The real-world applications of tDCS have been suggested by other researchers, including the use of it to enhance search behaviour in military personnel (Levasseur-Moreau, Brunelin, & Fecteau, 2013; McKinley, Bridges, Walters, & Nelson, 2012). Further, they also demonstrate that tDCS combined with statistically bound search arrays may be used as a rehabilitation technique, with ARPC and CRPC stimulation working together to enhance search towards the left hemispace in large-scale spaces. However, further research is needed to validate the technique, as well as developing an in-depth understanding of how tDCS effects both the intact and disrupted brain, its long-term and short-term effects, and the individual differences involved in current uptake and dispersal. Creating universal electrode montages and testing them under varying cognitive tasks may advance tDCS research further, as well as assist researchers to design testable predictions in the appropriate directions.

To conclude this research, using a range of spatial learning measures probability cueing was established in: 2D, visual search; virtual, representational space; and large-scale full-body search. The RPC may support probability cueing, especially in an environment that requires great physical effort. A saccadic explanation may not account for the allocation of the attention in such complex environments. The RPC may also support general search efficiency across environments varying in their complexity, task demands and qualities. Overall, these studies demonstrate how a comprehensive and detailed approach should be taken when analysing behaviour so that the domain generality of it can be accurately assessed. They also emphasise how non-invasive stimulatory techniques could be used as potential tools to identify important brain-behaviour relationships. There are still unanswered questions regarding the functional

basis, neural correlates and interaction of probability cueing within differing environments, leaving further research open to explore this attentional effect in detail.

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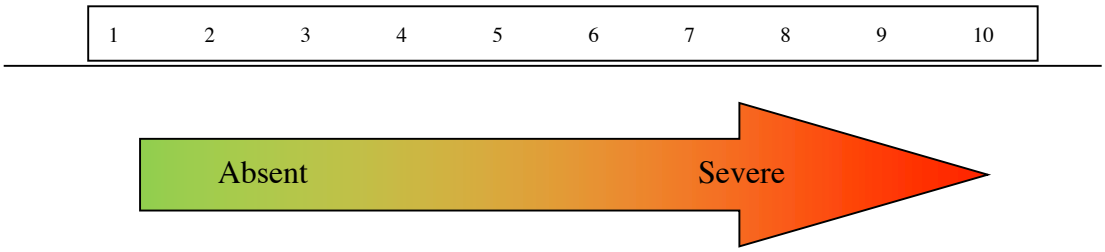
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tDCS Safety Questionnaire

This questionnaire will be filled in before receiving tDCS stimulation and after.

Please enter a value from 1-10, ranging from absent to severe, in the 'Rating' space below in response to the question: "Do any of these statements currently apply to you?". It is important that you answer all questions truthfully:



Do any of these statements currently apply to you?	Rating		Notes
	Before tDCS	**After** tDCS	
Headache			
Neck pain			
Back pain			
Blurred vision			
Scalp irritation			
Tingling			
Itching			
Increased heart rate			
Burning sensation			
Hot flush			
Dizziness			
Acute mood change			
Anxiety			
Others (specify in notes):			

tDCS Screening Questionnaire

It is important that you answer all of the following questions truthfully.

If any of the questions/terms on this form are unclear, or if you are unsure how to answer them, please do not hesitate to ask the Primary Investigator of the study.

	Yes	**No**
Have you ever had a seizure?		
Have you ever had a head injury resulting in a loss of consciousness that has required further investigation (including neurosurgery)?		
Do you suffer from Migraines?		
Do you currently have a medical diagnosis of a psychological or neurological condition which requires medication?		
Do you have any metal in your head (outside of the mouth) such as shrapnel or surgical clips?		
Do you have any implanted devices (e.g. cardiac pacemaker, brain stimulator)?		
Do you have a skin condition on your scalp? (e.g. psoriasis)		
Do you have a head wound that has not completely healed?		
Have you ever had an adverse reaction to tDCS?		
For female participants: Is there the possibility that you might be pregnant?		
Are you currently taking any prescribed medications, other than the contraceptive pill?		

The possible hazards of tDCS have been explained to me, and I understand that I can withdraw at any point for any reason, and that I do not have to disclose the reason(s) to the experimenter. By signing below I acknowledge that I understand this screening form and attest to its accuracy.

Participant's signature	**Researcher's signature**	**Date**

EHI Questionnaire and scoring

- Please indicate your preferences in the use of hands in the following activities by putting a tick in the appropriate column.
- Some of the activities listed below require the use of both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.
- Please try and answer all of the questions and only leave a blank if you have no experience at all with the object or task.

	Always left hand	*Usually left hand*	*No preference*	*Usually right hand*	*Always right hand*
Writing	☐	☐	☐	☐	☐
Drawing	☐	☐	☐	☐	☐
Throwing	☐	☐	☐	☐	☐
Scissors	☐	☐	☐	☐	☐
Toothbrush	☐	☐	☐	☐	☐
Knife	☐	☐	☐	☐	☐
Spoon	☐	☐	☐	☐	☐
Broom (upper hand)	☐	☐	☐	☐	☐
Striking match (match)	☐	☐	☐	☐	☐
Opening box (lid)	☐	☐	☐	☐	☐

The EHI scores were calculated using an amended scoring system (Schacter, 2000) in which each item was given a score of -10, -5, 0, +5 or +10, according to the answer given by the participant. These scores were then totalled, producing a composite score of the strength of lateralisation (with scores around 100 representing strong right lateralisation, -100 representing strong left lateralisation, and 0 representing no strong preference).

Experiment 5, Pairwise comparison results I

Pairwise comparisons for the main effect of block

Block	Block	Significance value
1	2	< 0.001
	3	< 0.001
	4	< 0.001
	5	< 0.001
	6	< 0.001
2	1	< 0.001
	3	< 0.001
	4	< 0.001
	5	< 0.001
	6	< 0.001
3	1	< 0.001
	2	< 0.001
	4	.057
	5	< 0.001
	6	< 0.001
4	1	< 0.001
	2	< 0.001
	3	.057
	5	.012
	6	< 0.001
5	1	< 0.001
	2	< 0.001
	3	< 0.001
	4	.012
	6	>1
6	1	< 0.001
	2	< 0.001
	3	< 0.001
	4	< 0.001
	5	>1

Experiment 5 – Pairwise comparisons results II

Simple Effects Analysis, examining the effect of block at each level of probability.

Probability	Block	Block	Significance values
Cued	1	2	< 0.001
		3	< 0.001
		4	< 0.001
		5	< 0.001
		6	< 0.001
	2	1	< 0.001
		3	< 0.001
		4	< 0.001
		5	< 0.001
		6	< 0.001
	3	1	< 0.001
		2	< 0.001
		4	.003
		5	< 0.001
		6	< 0.001
	4	1	< 0.001
		2	< 0.001
		3	.003
		5	< 0.001
		6	< 0.001
	5	1	< 0.001
		2	< 0.001
		3	< 0.001
		4	< 0.001
		6	.299
	6	1	< 0.001
		2	< 0.001

		3	< 0.001
		4	< 0.001
		5	.299
Uncued	1	2	.167
		3	.010
		4	< 0.001
		5	< 0.001
		6	< 0.001
	2	1	.167
		3	>1.00
		4	.245
		5	.014
		6	< 0.001
	3	1	.010
		2	>1.00
		4	>1.00
		5	.442
		6	.024
	4	1	< 0.001
		2	.245
		3	>1.00
		5	>1.00
		6	.908
	5	1	< 0.001
		2	.014
		3	.442
		4	>1.00
		6	>1.00
	6	1	< 0.001
		2	< 0.001
		3	.024
		4	.908
		5	>1.00