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FACULTY OF SOCIAL, HUMAN AND MATHEMATICAL SCIENCES

Psychology

Individual Differences in Dynamic Visual Search

by

Alexander Muhl-Richardson

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ABSTRACT

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Many real-world tasks involve interacting with a range of electronic visual displays. Maintaining rapid and accurate performance on such tasks may be difficult due to situational stress, time-pressure, and an awareness of high error-costs. In a typical visual search, relevant target items must be identified amongst irrelevant distractors, but in a dynamic display all of these stimuli may undergo change. Much of the literature on visual search and monitoring examines static arrays and scenes, but dynamic displays present a more complex problem that involves greater demands on sustained attention and higher levels of both spatial and temporal uncertainty. The present thesis investigates visual search and monitoring using a novel dynamic search task and examines some of the individual factors that influence performance on this task. Chapter 1 provides a general introduction and review of the literature on visual search, relevant individual factors and two potentially beneficial interventions. Chapter 2 introduces and characterises a novel dynamic search task and, across three experiments, demonstrates predictive monitoring and

the importance of individual differences in verbal working memory capacity and intolerance of uncertainty in accounting for variation in search performance. Chapter 3 shows that working memory training and transcranial direct current stimulation were not effective in improving search performance, but does reveal that target prevalence influenced target detection, predictive monitoring and the relationship between intolerance of uncertainty and search performance. Chapter 4 demonstrates similarities in the monitoring of colour and numerical information and shows that the need to search for a second category of target can have a negative impact on search performance and predictive monitoring. Finally, Chapter 5 summarises the findings from the empirical work in the preceding chapters and identifies a number of important theoretical and practical implications. Further work should continue to examine the contribution of individual variation in cognitive, personality and psychopathological traits to performance in complex visual tasks.

"You can't argue with the little things,

it's the little things that make up life."

Hank Scorpio

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<u>Declaration of Authorship</u>

I, Alexander Muhl-Richardson, declare that the thesis entitled *Individual Differences in Dynamic Visual Search* and the work presented in the thesis are my own, and have been generated by me as the result of my own original research. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University;
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
- Where I have consulted the published work of others, this is always clearly attributed;
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
- I have acknowledged all main sources of help;
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
- Either none of this work has been published before submission, or parts of this work have been published as:
    - Chapter 2: Muhl-Richardson, A., Godwin, H. J., Garner, M., Hadwin, J. A., Liversedge, S. P., & Donnelly, N. (in press). Individual Differences in Search and Monitoring for Color Targets in Dynamic Visual Displays. *Journal of Experimental Psychology: Applied*.
    - Note: the work in Chapter 4 is under review at *Applied Cognitive Psychology*

Signed: ………………………………………………………………………..

Date:…………………………………………………………………………….

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Abbreviations

ACT	-	Attentional Control Theory
ADHD	-	Attention Deficit Hyperactivity Disorder
ALTM	-	Activated Long Term Memory
ANT	-	Attention Network Test
BD	-	Background Distractor
CDT	-	Change Detection Task
D	-	Distractor
DLPFC	-	Dorsolateral Prefrontal Cortex
DTC	-	Dual-target Cost
EEG	-	Electroencephalogram
ERP	-	Event-related Potential
FIT	-	Feature Integration Theory
FMRI	-	Functional Magnetic Resonance Imaging
FVF	-	Functional Visual Field
GAD	-	Generalised Anxiety Disorder
GLMM	-	Generalised Linear Mixed Model
GS	-	Guided Search
HD-tDCS	-	High-definition Transcranial Direct Current Stimulation
IFG	-	Inferior Frontal Gyrus
IU	-	Intolerance of Uncertainty
IUS	-	Intolerance of Uncertainty Scale
LMM	-	Linear Mixed Model
LTM	-	Long Term Memory

PET	-	Processing Efficiency Theory
PFC	-	Prefrontal Cortex
SDT	-	Signal Detection Theory
SOS	-	Satisfaction of Search
SSM	-	Subsequent Search Misses
STAI	-	State-trait Anxiety Inventory
T	-	Target
TACS	-	Transcranial Alternating Current Stimulation
TAM	-	Target Acquisition Model
TDCS	-	Transcranial Direct Current Stimulation
TMS	-	Transcranial Magnetic Stimulation
TPD	-	Target-predictive Distractor
TRNS	-	Transcranial Random Noise Stimulation
VA	-	Visual Acuity
WM	-	Working Memory
WMC	-	Working Memory Capacity

Chapter 1

Introduction and Literature Review

The present thesis explores visual search and monitoring within complex dynamic displays, a topic of both significant theoretical and practical importance. The search and monitoring of dynamically changing stimuli is an understudied area and our theoretical understanding of visual search is primarily based on evidence from tasks that involve static and unchanging stimuli. It is for the same reason that the study of dynamic visual search holds practical significance: static search tasks are not representative of the majority of real-world searches. Increasingly, in applied scenarios, individuals are required to search and monitor electronic visual displays of information. Often, such as in medical and military domains, such tasks involve significant error costs. The first goal of this thesis is to understand how targets are detected in dynamically changing displays and how this relates to what is already known about more standard search tasks. To address these questions, and subsequent goals, a novel dynamic visual search task is introduced.

The second goal of this thesis is to examine individual factors that may influence or predict dynamic search performance. The effective processing of information in complex visual displays is facilitated by a high working memory capacity (WMC) and high levels of attentional control (Wickens, 1992). Furthermore, situations with a high error cost may entail significant stress and anxiety (Warm & Parasuraman, 2008), and anxiety has been shown to interfere with both the allocation of attention (Bishop, 2009; Eysenck, Derakshan, Santos, & Calvo, 2007) and the maintenance of sustained attention (Parasuraman, 1979). However, some individuals, with high WMC, may be able to compensate for this interference (Eysenck et al., 2007). In addressing this second goal, individual differences in WMC, anxiety and related traits are the primary focus.

The third goal of this thesis is to explore the extent to which the search and monitoring of dynamic displays can be improved with targeted interventions. To this end, the efficacy of working memory (WM) training and transcranial direct current stimulation (tDCS) of the dorsolateral prefrontal cortex (DLPFC) are examined. Both computerised WM training and tDCS have the potential to improve WM and related executive functions (e.g., Falcone, Coffman, Clark, & Parasuraman, 2012; Klingberg, 2010), but via two very distinct mechanisms of action.

These three goals are addressed in the experimental work presented in a ‘three-paper’ format in Chapters 2, 3 and 4. The present chapter continues with a review of the literature on visual search and human vigilance, and will address what eye movements can reveal about search strategy, the deployment of attention, and errors in search. This chapter then considers how these processes are influenced by individual differences in WMC, anxiety and related traits, before a review of the literature in the burgeoning areas of WM training and tDCS.

1.1 Visual search

1.1.1 Early visual search literature. Early studies of visual search sought to understand how the relationships between the features of objects, such as differences and similarities in colour, shape and brightness, affected search performance. A common finding was that high heterogeneity, on multiple feature dimensions, of stimulus displays typically increased search times (Eriksen, 1952, 1953; Green & Anderson, 1956). Other work examined search for multiple targets and related practice effects, finding that, with practice, search for up to ten targets simultaneously could be just as fast as search for a single target (Neisser, 1964; Neisser & Lazar, 1964; Neisser, Novick, & Lazar, 1963). It was generally found that, while search times were initially proportional to the number of targets, with practice this stops being the case (Kaplan & Carvellas, 1965). This early work provided some insight into the search guidance afforded by simple features, the relationships between different objects and the effects of practice. It also showed that some searches were performed more quickly and efficiently than others. This distinction, made in terms of fast, efficient, parallel search processes, and slow, inefficient, serial search processes, became a key component of Feature Integration Theory (FIT; Treisman & Gelade, 1980), the first comprehensive model applied to visual search.

1.1.2 Feature Integration Theory. An initial series of experiments conducted by Triesman and others (Treisman, Sykes, & Gelade, 1977; Treisman, 1977) showed clear differences between the search for targets defined by a single feature, such as colour, and those defined by a conjunction of multiple features, such as colour and orientation. Search slopes (search time per item) increased linearly for conjunction searches and non-linearly, and to a significantly lesser extent, for single feature searches. FIT breaks search down into two separate stages, with an early, pre-attentive, stage, involving fast parallel processing and a later attentive stage, involving slower serial processing. A completely parallel search would generate flat slopes, as search time would be independent of the number of items. A completely serial search would generate a linear function with time increasing with a greater number of items, as each item is inspected individually. Observed differences in search slopes shows that searches can proceed in parallel and in serial under different circumstances

In FIT, features are processed in the early parallel stage, prior to the active deployment of attention. Objects are processed later, in the serial stage, as they require focused attention. If a target can be identified easily and on the basis of a single feature, then this may preclude the need for a serial search and the target may ‘pop-out’ to a searcher. However, if this is not possible potential targets must be examined serially. In FIT, the parallel and serial stages are separate, and the parallel stage does not influence the later serial stage. Unfortunately, this results in predictions about search for targets defined by a conjunction of three features that are not consistent with the evidence. Specifically, FIT predicts that search for triple conjunction targets will be slow, however, this type of search can be accomplished quickly, because it is possible to identify a subset of stimuli in parallel and then search these stimuli serially (Wolfe, Cave & Franzel, 1989). The binary distinction between parallel and serial search processes is one that still persists within the literature and it has been suggested that an overreliance on search slopes (as a measure of attentional involvement) has contributed to this way of thinking (Kristjánsson, 2015). However, the degree to which a search is parallel or serial is better considered as a continuum rather than a dichotomy (Wolfe, 2016).

1.1.3 Attentional Engagement Theory. Search efficiency as a continuum is a central component of Attentional Engagement Theory (also known as similarity theory; Duncan & Humphreys, 1989). This model explains search in terms of not only the similarity between targets and distractors, but also the similarity between distractors and other distractors – a consideration not made in FIT. The first stage of this model is 'perceptual description', where visual input is processed and segmented into object representations. Objects then compete for access to visual short-term memory so that they might form the basis of a response. The weighting of objects in this competition is influenced by target-distractor similarity, because highly target-similar distractors will match target templates more closely, and distractor-distractor similarity, because groups of homogenous distractors can be suppressed more easily than heterogenous distractors. Under this model, search efficiency varies along a continuum according to the level of difficulty presented by these two forms of similarity. This model shares some ground with the Guided Search (GS) model, which also discards the serial-parallel dichotomy to avoid the shortcomings of FIT (Wolfe et al., 1989).

1.1.4 Guided Search. GS attempts to explain how information from early, pre-attentive, parallel search processes can guide the allocation of focused attention, in later serial search, such as in the case of search for triple feature conjunction targets. Under GS 4.0, the most recent version of this model, object recognition is a serial process, access to which is via a bottleneck controlled by selective attention and guided by various attributes (Wolfe, 2007). When an object is selected, information begins to be accumulated and potential target identification or rejection occur when this information reaches particular thresholds. The metaphor of a carwash is used to describe this process of accumulation. Information on multiple items can be accumulating, or progressing through the 'carwash', simultaneously, but only a single item, or 'car', can start this process at a time. Some tasks, such as those that involve extracting the 'gist' of a scene, do not require access to this bottleneck and are accomplished via a separate pathway.

In GS, selective attention, and subsequent access to object recognition processes, is guided by both bottom-up and top-down factors. This is accomplished via an activation map that combines bottom-up salience with activity that represents the extent to which stimulus features match the desired target properties. GS 4.0 only implements orientation and colour as guiding attributes, but others, including motion and size, are assumed to function similarly (Wolfe & Horowitz, 2017). GS 4.0 is able to account for a number of complex visual search effects, including effects of set size, target presence/absence, target-distractor similarity, array heterogeneity, linear separability, asymmetry, target categories and guidance. Although GS is not a model of eye movement control, and is based on the valid assumption that search does not *require* eye movements, visual search does normally involve eye movements (Klein & Farrell, 1989). The shifts of selective attention that are considered in GS would usually entail eye movements for the sequential fixation and inspection of stimuli. This review will now consider eye movement control in visual search and models which give accounts of visual search in the context of eye movements.

1.1.5 Eye movement control in visual search. The fovea is the region of the retina with the highest visual acuity and outside of the fovea acuity declines rapidly (Rayner, 1998). The fovea is small, and saccadic eye movements are therefore required to bring different objects into high resolution vision. During the course of a visual search, the eyes typically make saccades and fixate upon different stimuli within the environment or search array. Recording eye movements and fixations can provide an accurate and on-line measure of overt visual attention and thereby provide insight into the deployment of attentional resources during visual search. The nature of eye movements in visual search is highly task specific and depends upon the search array, for example, complex and crowded arrays are associated with a greater number of longer fixations, shorter saccades, and a reduced perceptual span (Vlaskamp & Hooge, 2006). In irregular or randomly organised arrays, stimulus features provide strong bottom-up guidance (Williams, 1966) and, as in reading, there is also an influence of present fixation on subsequent saccadic accuracy (Trukenbrod & Engbert, 2007).

Bottom-up sources of guidance have been the starting point for a number of models of eye movement control in search, and eye movement control in visual search has been modelled in a purely bottom-up fashion using saliency maps (Itti & Koch, 2000). In this kind of model, eye movements are directed towards the most active location on a saliency map, determined by a combination of local contrasts across a number of feature dimensions (e.g., intensity, colour, orientation, etc.). An eye movement is made to the most active location on the map, i.e., that of the highest salience, and previously fixated locations are inhibited.

Other models have been based upon stimulus-driven saliency maps, but allow for some degree of top-down control (e.g., Findlay & Walker, 1999; Findlay & Gilchrist, 2003) or divide stimulus-driven and goal-driven control into separate stages, with bottom-up effects occurring early and before goal-driven control (Zoest, Donk, & Theeuwes, 2004). While purely stimulus-based models can accurately predict search performance in some tasks, they may struggle in more complex, naturalistic tasks with multiple target types or varying levels of target prevalence, where top-down factors can contribute to the use of different eye movement strategies. The Target Acquisition Model (TAM) provides an account of eye movements in searches for specific targets and has been successfully applied to complex, real-world, scenes and stimuli (Zelinsky, 2008). In TAM, eye movements are made according to the geometric average of activity on a 'target map', when the proximity of a proposed fixation location crosses a certain threshold. Unlike a saliency map, the target map is the product of bottom-up *and* top-down factors, with activity determined by comparisons between a target representation and features within the visual scene. While TAM accurately models patterns of fixations within complex natural scenes and accounts for realistic errors in eye movement control (Zelinsky, 2012), it is limited in so far as it does not attempt to model fixation durations.

Recently, another model was proposed that offers a combined explanation of guidance and eye movements in visual search, by focusing on fixations as the basic unit around which search performance should be measured (Hulleman & Olivers, 2017). The authors argue that fixations should not simply be ignored because search *can* proceed without them and that the item, the basis of search slopes, is often unimportant, for example in singleton detection and decisions about regions or groups of stimuli. The framework is based around the assumption of a functional visual field (FVF). The size of the field is dependent upon the difficulty of target discrimination (lower discriminability entails a smaller FVF), but within the FVF all items are processed in parallel. The model also incorporates some limited inhibition of previously fixated regions and a stopping rule based on the proportion of items examined. Within this model, search is not guided by the features of individual items, but by any discriminable property of the search array within the FVF for a particular fixation. The authors note that this model can also be applied to searches that do not involve any eye movements, as even those searches must involve a single *fixation,* even if they don't involve any saccades. A number of issues were raised in the peer-commentary accompanying the original publication of this model, including how it is determined what features are bound to specific items, how and when adjustments to the size of the FVF are controlled and measured, and how variation in fixation duration might be accounted for. It is likely that a more comprehensively implemented version of this model would be better able to address some of these criticisms. However, in its current form it still represents a useful alternative to item-based accounts that deliberately set eye movements apart from search.

1.1.6 Eye movement and search strategies. The features of a search task can influence the approach or strategy adopted by individual searchers. For example, in a simple conjunction search task subjects were found to: have limited awareness of perceptual grouping; not know whether their attention had been captured by a singleton in the search displays; and be unable to accurately assess their search strategy (Proulx, 2011). These effects can cause participants to ignore previously given instructions to adopt a particular strategy without conscious awareness. However, in circumstances when searchers are able to make use of prior knowledge or instruction, for example, to allow some degree of prediction or to reduce uncertainty regarding the appearance of targets, they typically perform better (Eckstein, 2011).

Location-based probabilities and predictive pre-cues influence search behaviour, and target detection can be improved when targets appear in high-probability locations or when target onsets are preceded by valid cues (Druker & Anderson, 2010; Geng & Behrmann, 2005). These effects hold for a variety of both simple stimuli, and more complex ones like Gabor patches (Posner, Snyder, & Davidson, 1980; Smith, Ratcliff, & Wolfgang, 2004). Contextual cueing, where a target cue is provided by the context of a set of distractors, can also serve to improve search performance on subsequent exposures to the same stimulus configurations (Chun & Jiang, 1998). In the case of naturalistic scenes, learned rules and likelihoods regarding object co-occurrences can have a significant impact upon search performance, for example, one is most likely to find a car on land rather than in the sky and a searcher would typically limit their search accordingly, excluding a significant area of the scene (Neider & Zelinsky, 2006).

Eye movements provide a detailed record of what regions of stimuli have received overt attention during search and can reveal strategic differences independently of conscious awareness. In particular, the eye movements of experts have long been shown to differ from those of novices in a variety of domains, including the search of radiological images (Kundel & La Follette, 1972), piloting aircraft (Bellenkes, Wickens, & Kramer, 1997) and in goalkeeping in association football (Savelsbergh, Williams, Kamp, & Ward, 2002). It has also been demonstrated, again across multiple domains, that showing novices the eye movement recordings of experts boosts the effectiveness of standard training and leads to improved performance (Litchfield, Ball, Donovan, Manning, & Crawford, 2010; Mackenzie & Harris, 2015).

The optimal eye movement strategy is contingent upon the demands of the task at hand. In a complex colour visual search task, where stimuli both moved and changed appearance, it was found that those who used a more passive strategy, involving fewer eye movements, typically performed better than those who searched more actively and made more eye movements (Becic, Kramer, & Boot, 2007; Boot, Kramer, Becic, Wiegmann, & Kubose, 2006). Furthermore, it was found that the performance of more active searchers could be significantly improved, simply by instructing them to make fewer eye movements. In a later study, it was also found that participants tended to adopt a stable eye movement strategy across tasks, even when this led to lower performance on individual tasks, however, when feedback was provided and performance was incentivised, participants were more adaptive in their eye movements between tasks (Boot, Becic, & Kramer, 2009). This is consistent with evidence from a static search task where participants only benefited from a contextual cueing effect when instructed to adopt a passive search strategy (Lleras & von Mühlenen, 2004). It appears that individuals can be predisposed towards a particular eye movement strategy but, with awareness and proper motivation, they can adapt to improve performance.

1.1.7 Target templates and working memory. The sections above describe some of the stimulus features, like colour and orientation, that can guide search, but this review has not explored in detail how search can be guided when the appearance of the desired target is known. While it is not the only model to include such a mechanism, Guided Search explains this type of search in terms of a target template that specifies a set of features for target identification (Wolfe, 1994, 2007). It has been suggested that target templates are stored in visual WM, where they are maintained during search, compared to visual stimuli, and updated if necessary (Beck, Hollingworth, & Luck, 2012; Carlisle, Arita, Pardo, & Woodman, 2011) . Also, the more precise the target template, the better the support for both search guidance and decision making (Hout & Goldinger, 2015). Studies have offered support for this role of visual WM in maintaining target templates on three fronts: (1) evidence of the disruption of search processes under conditions of WM load

(Attar, Schneps, & Pomplun, 2016; Hulleman & Olivers, 2014; Woodman & Luck, 2004); (2) event-related potentials (ERPs) indicative of WM engagement (Gunseli, Meeter, & Olivers, 2014; Woodman & Arita, 2011); and (3) attentional bias towards distractors that match the contents of WM (Han & Kim, 2009; Hollingworth & Luck, 2009).

Some recent studies have, however, raised issues that suggest the role of visual WM in maintaining target templates may not always be as straightforward as previous evidence suggested. It is estimated that visual WM has a capacity of 3 to 4 items and there is evidence that multiple target templates, within this capacity limit, can be maintained and offer guidance simultaneously, albeit at some cost (Beck et al., 2012; Stroud, Menneer, Cave, & Donnelly, 2012; Stroud, Menneer, Cave, Donnelly, & Rayner, 2011). 'Hybrid' visual and memory search refers to search that involves both a visual search of the environment *and* a search through set of possible target items stored in memory. Evidence from recent hybrid search studies show that search can be carried out for a set of targets that far exceeds the estimated capacity of visual WM (Wolfe, 2012; Wolfe, Aizenman, Boettcher, & Cain, 2016). The authors propose that, rather than being held in WM, targets are represented in an activated part of long-term memory (ALTM; Boettcher, Drew, & Wolfe, 2013; Drew, Boettcher, & Wolfe, 2016). Previous evidence regarding the involvement of WM in search cannot be ignored however, and even these authors found that performance in a concurrent WM task suffered while performing hybrid search (Drew et al., 2016). The suggested account acknowledges previous evidence and proposes that the role of visual WM is as a conduit via which relevant visual input enters long-term memory (LTM), where comparisons between the two can be made. Whether it is because of increased 'bandwidth' in carrying visual input to LTM or because there is more capacity available for carrying out template comparisons in WM, it remains true that individual variation in WMC is an important predictor of performance in many visual searches

(Gaspar, Christie, Prime, Jolicœur, & McDonald, 2016; Kane, Poole, Tuholski, & Engle, 2006; Peltier & Becker, 2016, 2017; Rajsic, Sun, Huxtable, Pratt, & Ferber, 2016).

1.1.8 Multiple target search. There are circumstances, common in the real-world, that may make search particularly challenging. This review will now consider a number of these, beginning with multiple target search. Searches in the real-world are rarely for a single item, search arrays often contain more than one target and more than a single target may be sought at once. The literature on multiple target search can be divided into these two distinct areas: one concerning search for two different possible targets in displays that contain a single target (e.g., Kaplan & Carvellas, 1965; Menneer, Barrett, Phillips, Donnelly, & Cave, 2007), sometimes termed 'multiple-category search' (Fleck, Samei, & Mitroff, 2010); and one concerning search for a single type of target in displays that contain multiple target instances (e.g., Fleck et al., 2010; Körner & Gilchrist, 2008). The distinction between these two lines of research can sometimes be confusing and there has been overlap between the two (e.g., Duncan, 1980), however, it should be made clear that both cases of multiple target search described above are distinct from multiple feature (or feature conjunction) search (Treisman & Gelade, 1980), where targets are defined by conjunctions of multiple features.

Satisfaction of search (SOS), or subsequent search misses (SSM), refers to a particular effect encountered in search of displays that contain more than one target when a subject must search for all targets, whereby after one target is found in a display, any further targets present in the display are significantly less likely to be found (Biggs, 2017; Cain, Adamo, & Mitroff, 2013). SOS was first established in the radiographic literature (Berbaum, Franklin, Jr., Caldwell, & Schartz, 2010), a domain in which search misses may have severe results, for example, an incorrect cancer diagnosis. Early work in this area was based upon the assumption that these errors resulted from searchers becoming 'satisfied' after finding an initial target and not detecting additional targets (Tuddenham, 1962), but more recently it has been suggested that these errors may result from depleted cognitive resources, such as WM, arising from the task of detecting an initial target (Cain & Mitroff, 2013). The SOS effect has been shown to be dependent upon the similarity of subsequent targets and subjects' expectations about target frequency or prevalence (Biggs, Adamo, Dowd, & Mitroff, 2015; Gorbunova, 2017). For example, when the frequency of two target trials is reduced compared to single-target trials, a strong SOS effect is observed (Fleck et al., 2010). In a study that used eye tracking to categorise the different errors responsible for SOS effects, it was found that over a third of errors in searches for two targets were simply due to the second target not being fixated (Cain et al., 2013). Other errors included those where a second target was fixated but no response was made and those where targets that had already been found were refixated. While some real-world tasks may involve searching only for a single type of target, often search involves numerous target categories and this presents a different set of difficulties.

The dual-target cost (DTC) is found when searching for more than one type of target (multiple-category search) and is typically studied using search arrays that contain only one target. In a dual-target search task where participants searched for up to two possible square targets defined by colour, it was found that there was a significant cost in both accuracy and response times when participants search for two possible targets compared to search for a single target (Menneer, Phillips, Donnelly, Barrett, & Cave, 2004). Response times for dual-target search were also significantly longer than aggregated times from two single-target searches. The DTC has been observed in search for more complex stimuli, such as abstract shapes resembling images found in x-ray baggage screening (Menneer, Stroud, Cave, Donnelly, & Rayner, 2008, p. 175) and real x-ray baggage screening images where participants searched for threat items such as handguns, knives and improvised explosive devices (Menneer, Cave, & Donnelly, 2009). In simpler search tasks, with sufficient practice the DTC in response time was eliminated, although the cost in terms of accuracy remained, but, in the more complex search task used by Menneer et al. (2009), practice did not eliminate either aspect of the cost.

Examining the DTC has provided insight into the nature of the target representations that are used to guide search. In the case of colour search, this cost arises when both targets are not linearly separable from distractors in colour space, for example, when targets are defined by the colours red and yellow and distractors are orange (D'Zmura, 1991). A similar basis for costs in shape and orientation search has been suggested (Menneer et al., 2007). Using eye-tracking, it was found that during search for two different colours many more irrelevant distractors are fixated compared to search for a single colour, but that search improves if the two targets share a colour (Stroud et al., 2011). In a later study, the difference between two colour targets was manipulated in a dual-target search task, such that the colours could be a number of 'steps' away from each other in colour space (Stroud et al., 2012). Search performance and eye movements suffered to a greater extent when the two targets were separated by more steps, but improved when targets were more similar. These effects are consistent with this type of dual-target search being guided a separate representation for each of the two targets, even when both targets are highly similar. These results are also consistent with search for similar targets being guided by a single broad target representation. However, there is no evidence for an additional modes of target representation and the most parsimonious account suggests the same mechanism in both cases, consistent with other eye movement and behavioural evidence (Barrett & Zobay, 2014; Beck et al., 2012; Irons, Folk, & Remington, 2012).

Multiple targets and multiple target categories are common occurrences in real-world search tasks, such as radiographic image search and x-ray baggage screening. Both interfere with search in different ways, including perceptual biases, cognitive biases and management of target representations, but in both cases the interference stems from top-down factors. In this respect, a similar source of interference in search is variation in target prevalence.

1.1.9 Prevalence effects. The prevalence effect poses another challenge to effective search, again driven by real-world considerations and drawing upon scenarios such as radiographic screening and airport baggage scanning (for a review see Horowitz, 2017). In these real-world scenarios, where targets are rare but accurate detection is crucial, it has been found that the frequency with which a target is present, or its prevalence, can impact target detection. Typically search experiments use designs where targets are present on half of all trials (50% prevalence), however, as target prevalence decreases, participants begin to make many more miss errors.

Initial results suggested a speed-accuracy trade off with responses being made before displays were fully searched (Fleck & Mitroff, 2007; Wolfe, Horowitz, & Kenner, 2005). While, in some cases, prevalence effects may be attributable to motor priming or simply premature termination of search (Rich et al., 2008), combined evidence from a number of studies suggests that prevalence effects are, in the terms of Signal Detection Theory (SDT), primarily a result of a shift in response criterion (Godwin, Menneer, Cave, & Donnelly, 2010; Godwin, Menneer, Riggs, Cave, & Donnelly, 2015; Macmillan & Creelman, 2009; Wolfe et al., 2007). In low prevalence conditions, subjects adjust their response criterion such that they require more evidence before making a ‘target present’ response, as this response is incorrect most of the time. However, in some cases, dependent on task, prevalence effects may also be attributable to motor priming or simply premature termination of search (Rich et al., 2008). Participants appear to adjust their response criterion according to both a subjective perception of their own performance and also explicit feedback when this is available (Schwark, Sandry, Macdonald, & Dolgov, 2012; Wolfe et al., 2007) and these adjustments can be finely tuned at prevalence levels of less than 1% (Mitroff & Biggs, 2014). Prevalence effects can be found in a wide variety of tasks, including those with real-world stimuli and dynamic elements (Harris et al., 2015). The majority of studies of target prevalence have involved static search tasks, however, evidence from dynamic tasks is important in establishing the role of effects like those of prevalence and multiple targets in the real-world, where objects rarely stay the same and often move or change over time.

1.1.10 Dynamic search. Stimuli can be dynamic in two distinct, but not mutually exclusive, respects: (1) changing state and (2) being in motion. In either case, however, it remains true that static search arrays are limited in the extent to which they represent real-world searches. To address this problem, some studies have examined dynamic search tasks in some highly applied contexts like driving and closed-circuit television (CCTV) viewing (Howard, Troscianko, & Gilchrist, 2010; Howard, Troscianko, Gilchrist, Behera, & Hogg, 2013). Other studies have incorporated dynamic features into traditional search tasks, for example, to examine the guidance offered by features like motion and luminance changes (Hillstrom & Yantis, 1994; Jonides & Yantis, 1988).

Object motion, like other features such as colour and shape, can be used to guide search (Triesman & Gelade, 1980; McLeod, Driver & Crisp, 1988). There is however variation in the quality of this guidance, for example, a fast moving target among slow distractors has a high degree of pop-out, but this is not the case for a slow moving target among fast distractors (Ivry & Cohen, 1992). Dynamic onsets/offsets and luminance changes can also guide search (Theeuwes, 2004). Static stimuli have been shown to ‘pop out' from dynamically changing distractors that onset and offset repeatedly, but not when distractors remain present and only change in luminance (Pinto, Olivers, & Theeuwes, 2006) and abrupt onsets and changes in luminance have been associated with involuntary attentional capture (Hillstrom & Yantis, 1994; Jonides & Yantis, 1988; von Mühlenen & Conci, 2016; von Mühlenen, Rempel, & Enns, 2005). A recent series of experiments was conducted using a search task that incorporated large set sizes, motion and luminance changes in an effort to be more representative of real-world searches (Kunar & Watson, 2011, 2014). In these experiments, motion interfered with search, reducing efficiency and increasing error rates, and abrupt luminance changes only captured attention when they were unique. Similarly, recent experiments involving the search of stimuli that undergo dynamic changes in orientation found accuracy to be significantly impaired relative to a comparable static task (Jardine & Moore, 2015). These results are an important reminder of the limits to the generalizability of findings observed in simple static search tasks.

A prominent use of dynamic stimuli in the visual search literature has been the study of memory in search, where moving stimuli have been used to disrupt location- or object-based tagging. Memory for previously searched locations, in the form of some kind of tagging process, can facilitate efficient search by minimising the resources that are wasted re-attending to old locations (Posner & Cohen, 1984). It has been suggested that an 'inhibition of return' mechanism, that prevents or reduces re-attending to previously attended stimuli, may stem from processes involved in foraging (Klein, 1988; Klein & MacInnes, 1999).

A notable set of experiments examined the role of memory in search using a novel search task involving stimuli that randomly changed position at regular intervals (Horowitz & Wolfe, 1998, 2003). The authors reasoned that, if search involved memory for previously attended locations, then the dynamic nature of this task should interfere with this process. No difference was found between search in dynamic and static conditions, which suggested a memory-free search. However, it has since been suggested that these conclusions were based upon the weak premise that the same strategy was employed in both static and dynamic search conditions (Shore & Klein, 2000). Later work used eye tracking to provide an unambiguous assessment of overt visual attention and, therefore, a clear determination of whether individuals returned to previously attended locations. While participants were found to refixate some objects, this did not occur to the extent predicted by a memory-free search and was consistent with revisits to items that had not been adequately processed on the first fixation (Peterson, Kramer, Wang, Irwin, & McCarley, 2001). The inconsistent findings of Horowitz and Wolfe (1998, 2003), in comparison to the rest of the literature, have been explained in terms of divergent strategies adopted by participants between the dynamic and static tasks (von Mühlenen, Muller, & Muller, 2003). The extent to which location- or object-based tagging can occur appears to be task-specific. In some simpler search tasks with moving stimuli, some form of inhibitory tagging does appear possible, but breaks down when stimulus movement becomes more complex and less predictable (Hulleman, 2009). In any case, dynamic search tasks typically require that attention be sustained, and that searchers remain vigilant, over a longer time period while monitoring changes to stimuli.

1.2 Vigilance

Vigilance refers to the ability to sustain attention on a task over an extended period of time (Davies & Parasuraman, 1982). Examples of this type of task, relating to early work in the area, often include military watch duty and radar screen monitoring. An important theoretical framework in considering effects related to vigilance is Signal Detection Theory (SDT), which was briefly mentioned during the earlier discussion of prevalence effects.

1.2.1 Signal Detection Theory. Vigilance tasks are often described within the framework of SDT. This approach is applicable to any task that involves two discrete states or types of information that must be distinguished from one another, where an observer must respond whether a stimulus is a signal/target or noise/distractor (Macmillan & Creelman, 2009). A response can be classified in one of four ways: (1) correctly responding target is a 'hit'; (2) not responding to a target is a 'miss'; (3) responding to a non-target as if it were a target is a 'false alarm'; and (4) correctly responding to a non-target is a 'correct rejection' (Wickens, 1992). Performance can therefore be considered in terms of hit and false alarm rates, but, within SDT, this information can also be used to generate two key measures: criterion (c) and sensitivity (d'). The response criterion is a threshold that an observer sets for themselves and determines the decision they make about whether or not a target or signal is present. This decision is informed by perceptual 'evidence' about a stimulus - if the evidence is sufficient and above the threshold, a 'target present' response will be made, and if it is insufficient and below it, a 'target absent' response will follow. The second measure of sensitivity, or discriminability, is how easily a signal can be distinguished from noise. These two parameters can change over time to reflect changes in the task and learning by the observer. Together, they can be used to provide insight into what contributes to variation in performance within a given task.

1.2.2 The vigilance decrement. The vigilance decrement refers to the decrease in performance, in terms of hit rate, in tasks that require monitoring or sustained attention (Warm, Finomore, Vidulich, & Funke, 2015; Warm & Parasuraman, 2008). There are many applied scenarios, in a variety of domains, where a consistently high level of vigilance is at least desirable, if not imperative. The vigilance decrement can be described primarily in terms of a shift in response criterion such that an observer is biased towards not making a response (responding 'target absent') and therefore being more likely to miss targets. It can also be associated with a reduced sensitivity or discriminability for targets in cases of ‘successive discrimination’, where a stimulus must be compared against a target representation in memory (Parasuraman, 1979).

Vigilance can be assessed in different sensory modalities. Auditory, visual, and tactile stimuli have all been used in previous research and no sensory modality is immune to a decrement in vigilance over time (Davies & Parasuraman, 1982). Stimulus complexity and the number of possible sources of signal that need to be monitored in a given task affect the rate of decrement (Parasuraman, 1979). The rate of the decrement may be high when tasks are temporally complex, with rapid or irregular onset of stimuli, when tasks have high spatial complexity, and when tasks require stimuli to be compared to a target representation in memory. Indeed, the vigilance decrement is highly task specific, ranging from 30 minutes in the Mackworth clock test to 8 minutes in a more naturalistic scene based vigilance task (Helton & Russell, 2011; Mackworth, 1948). One study observed no specific performance decrement over time, either in terms of hit rate or response times, in a first-person video game target detection task (Szalma, Schmidt, Teo, & Hancock, 2014). This was despite the task entailing significant cognitive load, decreased engagement over time and increased distress. The authors of this study suggested that in some cases subjects may overcome continued task demands with compensatory effort. Variability also exists within the responses of individuals in vigilance tasks and response time variability appears to provide another indication of the vigilance decrement, with greater variability reflecting lapses in sustained attention (Rosenberg, Noonan, DeGutis, & Esterman, 2011).

The most prominent theory of vigilance performance is the resource depletion theory. This explains the vigilance decrement in terms of a limited set of attentional resources that are required by sustained attention tasks. As time progresses, these resources are depleted and cannot be refreshed or replenished while on task (Warm & Parasuraman, 2008). Other less well-established theories of the vigilance decrement include mindlessness theory and habituation theory. The mindlessness theory posits that over the time course of a sustained attention task, subjects become bored and begin to find the task monotonous, allowing attentional resources to be diverted to internal unrelated cognitions (Manly, Robertson, Galloway, & Hawkins, 1999). Habituation theory suggests that reduced goal-directed attentional control is due to difficulties in maintaining a task goal over a period of time and it is this goal habituation that is responsible for the vigilance decrement (Ariga & Lleras, 2011).

The resource-depletion theory is supported by evidence across different vigilance tasks, where errors were not primarily due to boredom or monotony (Helton & Russell, 2011). It is also supported by non-invasive brain stimulation work (J. T. Nelson, McKinley, Golob, Warm, & Parasuraman, 2014) and cerebral blood flow studies, which show decreases in neurophysiological arousal associated with decreases in sustained attention performance (Shaw et al., 2009; Warm & Parasuraman, 2008). This account is consistent with evidence that WM resources are required for effective vigilance performance (Caggiano & Parasuraman, 2004).

The vigilance decrement is often not considered within the visual search literature, but for any task that persists over an extended period of time, it is an important source of error that can potentially interact with multiple target or prevalence effects. If the vigilance decrement comes about due to a lack of available attentional resources, as the resource depletion account suggests, then some individuals may be more prone to lapses in sustained attention than others. In particular, those who experience situational stress or anxiety, which can also interfere with the ability to effectively allocate attention, may experience more rapid or larger lapses of attention.

1.3 Anxiety, Attention and Working Memory Capacity

There are many situations, when considering the biases and sources of error that have been mentioned in previous sections of this review, where it is important that attention is allocated effectively and efficiently. An additional factor that is highly likely to influence how this occurs, and one that is likely to be experienced in many real-world situations, is anxiety (Eysenck et al., 2007). Anxiety is a negative emotional state characterised by worrisome cognitions and increased awareness of threats to present goals (Eysenck & Calvo, 1992; Eysenck et al., 2007). A distinction that is relevant to the current review is that between trait anxiety, which reflects relatively stable personality characteristics, and state anxiety, an interaction between trait anxiety and situational stress (Eysenck & Calvo, 1992). Anxiety has been associated with two distinct types of attentional bias; selective attention to threat and hypervigilance for threat (Richards, Benson, Donnelly, & Hadwin, 2014).

1.3.1 Selective attention to threat. Selective attention to threat is characterised by rapid engagement and delayed disengagement from threatening stimuli (for a review of selective attention in the context of Generalized Anxiety Disorder [GAD] see Goodwin, Yiend, & Hirsch, 2017). Rapid engagement is sometimes referred to as vigilance for threat and delayed disengagement as attentional maintenance on threat. Evidence for these attentional biases has come from a variety of experimental tasks, including those using free association methods (Haney, 1973), emotional face stimuli (Richards, Hadwin, Benson, Wenger, & Donnelly, 2011) and dichotic listening (Burgess, Jones, Robertson, Radcliffe, & Emerson, 1981). Two common visual tasks within this body of literature are the emotional Stroop and dot-probe tasks (MacLeod, Mathews, & Tata, 1986; Mathews & Macleod, 1985; Mogg, Mathews, & Weinman, 1989).

In the emotional Stroop task, the colour of emotional words must be named, and the results reflect the level of emotional interference upon responses. Anxiety-relevant stimuli have been shown to interfere particularly with responses made by anxious participants and these results appear to be robust with respect to both supraliminal and subliminal presentation (Bradley, Mogg, Millar, & White, 1995; Mathews & Macleod, 1985; Mogg, Bradley, & Williams, 1995; Mogg et al., 1989). In the dot-probe task used by MacLeod et al. (1986), participants were required to detect dot probes presented on a visual display after they been shown words that were either threat related or non-threat related. They found that anxious individuals detected dots presented where threat words had been shown significantly faster than dots presented at another location. Anxious individuals have been found to be slower to respond than control subjects in a two alternative forced choice task when distractors could be neutral, positive, physically threatening or socially threatening words, suggesting difficulty disengaging from threat (Mathews, May, Mogg, & Eysenck, 1990). Further evidence for delayed disengagement from threat in anxious participants comes from a spatial orienting task with directly task-relevant threat that relates to the risk of losing points within the task (Derryberry & Reed, 2002).

While many studies have simply recorded participants' levels of trait anxiety before or after they have completed an attentional task, other studies have manipulated or induced situational stress in order to examine transient effects of state anxiety upon attention. State anxiety can interfere with the allocation of attention towards stimuli perceived as threatening, as well as negatively impacting performance on visual tasks with neutral stimuli. MacLeod and Mathews (1988) investigated the interaction of trait and state anxiety in attentional biases without an experimental manipulation, simply by taking advantage of situational factors in a university environment. While state anxiety was broadly higher immediately before an examination compared to a number of weeks before, they found a dissociation between high trait anxious individuals, who showed greater engagement with threatening stimuli, and low trait anxious individuals, who showed threat avoidant behaviour. Threat of electric shock has also been used to induce anxiety in subjects (Shackman et al., 2006). Just the threat of shock was found to be sufficient to increase state anxiety and decrease accuracy on a spatial WM task. For individuals with high trait anxiety, simply being in a laboratory environment was sufficient to elevate state anxiety. Other evidence suggests that, irrespective of trait anxiety, those under high stress show greater engagement with threat (Mogg, Mathews, Bird, & Macgregor-Morris, 1990), but this may be dependent upon specific stressors. Together, this evidence is consistent with anxiety, in the presence of threat, impairing the orienting attentional network, a set of neural areas involved in orienting to specific sensory information (Fan, McCandliss, Sommer, Raz, & Posner, 2002; Fan, McCandliss, Fossella, Flombaum, & Posner, 2005; Posner, 1980; Posner & Petersen, 1990; Posner & Rothbart, 2007).

1.3.2 Hypervigilance. In addition to the effects observed in the presence of threatening stimuli, anxious individuals also experience greater distraction in the presence of neutral and task-irrelevant stimuli (Richards, Benson, & Hadwin, 2012). This is consistent with an overall broadening of attention or hypervigilance and contrasts with the selective attentional engagement biases discussed above, where attention is narrowed and focussed on threatening stimuli (Gerdes, Alpers, & Pauli, 2008; Wieser, Pauli, Weyers, Alpers, & Mühlberger, 2009). It has been suggested that hypervigilance and selective attention are separate processes that operate in different situations (Richards et al., 2014). Hypervigilance appears to arise from an effect of anxiety upon the alerting attentional network, a set of neural areas that are involved in maintaining a state of alertness and readiness to respond (Fan et al., 2002, 2005; Posner & Petersen, 1990; Posner & Rothbart, 2007).

Hypervigilance may be characterized by either an increased number of eye movements, relating to excessive overt scanning, or a decreased number of eye movements, as individuals covertly broaden their attention (Richards et al., 2014). Sources of eye tracking evidence in this area are limited but anxiety has been associated with fewer eye movements and an improved ability to detect multiple targets, which is consistent with a broadened deployment of attention (Richards et al., 2011). The attention of anxious individuals has been shown to be more easily captured by peripherally displayed irrelevant and non-threatening, as well as threatening, distractors (Gerdes et al., 2008; Richards et al., 2012) and, in addition to a broadening of attention, anxiety has been associated with improved sustained attention over time (Grillon, Robinson, Mathur, & Ernst, 2016).

1.3.3 Intolerance of uncertainty. Intolerance of uncertainty (IU) is a personality trait that represents an individual's tolerance for uncertainty regarding the occurrence of potentially negative future events and is an important factor in worry, where anxiety is experienced in relation to such events (Buhr & Dugas, 2002, 2006; for a review see Carleton, 2016). IU is characterised by the perception that the possibility of potentially negative future events occurring is unacceptable and that ambiguous stimuli are threatening (Dugas, Freeston, & Ladouceur, 1997). Those with high IU will take steps to avoid or reduce uncertainty, including cognitive avoidance to reduce distressing thoughts and broader avoidance of potentially uncertain experiences (Koerner & Dugas, 2008). A recent meta-analysis identified two main components of IU, one of which encompasses prospective anxiety and a desire for predictability and the other of which relates to inhibitory anxiety and the inability to act (Birrell, Meares, Wilkinson, & Freeston, 2011). Most studies in this review used either the long or short version of the Intolerance of Uncertainty Scale (IUS), which is the most common means of assessing IU (Khawaja & Yu, 2010).

There is evidence that IU affects both the allocation of attention and decision making processes. IU was found to be related to vigilant coping (directly attending to and confronting threat), which may represent an effort to reduce ambiguity (Krohne & Hock, 2011). In a lexical visual search task, it was found that greater IU was associated with more rapid engagement with word stimuli that related to ambiguity or uncertainty (Fergus, Bardeen, & Wu, 2013). IU was also found to be positively associated with the alerting attentional network, which is responsible for maintaining a state of alertness (Fergus & Carleton, 2016). IU has been associated with decision making processes, with evidence from functional neuroimaging (Luhmann, Chun, Yi, Lee, & Wang, 2008) and behavioural tasks that involve uncertain outcomes and risk taking, such as the Wisconsin Card Sorting Test (Carleton et al., 2016). In a gambling task, it was also found that individuals with high IU were more likely to accept the possibility of an immediate but less valuable and less probable reward, rather than to wait for a more valuable and more likely reward at a later time (Luhmann, Ishida, & Hajcak, 2011). Together, this evidence suggests that IU may be important when considering performance in complex dynamic visual tasks. In such tasks, there is both spatial and temporal uncertainty surrounding the onset of target information and it may often be the case that waiting is part of an optimal strategy.

1.3.4 Processing Efficiency Theory. Processing Efficiency Theory (PET; Eysenck & Calvo, 1992) explains the impact of anxiety upon cognitive performance in terms of performance effectiveness and processing efficiency. Effectiveness relates to performance on a particular task, for example accuracy or response time, and efficiency reflects the level of cognitive resources required to attain a given level of performance. PET predicts that anxiety primarily impacts processing efficiency via worry, a component of state anxiety involving fear of failure and negative consequences (Eysenck, Derakshan, Santos, & Calvo, 2007). Whilst worrisome cognitions may place additional demand on WM resources, individuals may also be motivated to use a higher degree of effort to compensate for these effects, resulting in reduced efficiency but not necessarily reduced effectiveness. The theory suggests that the main effect of worry upon working memory is via the central executive, explaining why the detriment associated with anxiety is found in such a wide range of tasks. This is supported by evidence showing significantly reduced performance, in verbal reasoning tasks, in highly anxious participants when additional WM load was high (Eysenck & Derakshan, 1998; MacLeod & Donnellan, 1993). Specific support for the effect of anxiety upon the central executive comes from a corsi blocks task with a concurrent backwards counting task which revealed that anxiety had a differential effect upon WM task performance, only when the concurrent task targeted the central executive (Eysenck, Payne, & Derakshan, 2005).

1.3.5 Attentional Control Theory. Attentional Control Theory (ACT) was developed to address the specific effects of anxiety upon central executive function (Eysenck et al., 2007). ACT retains the distinction made in PET between processing efficiency and performance effectiveness, but describes the specific routes by which anxiety disrupts normal attentional control. As in PET, compensatory strategies, such as increased effort, may allow for a comparable level of performance effectiveness between anxious and non-anxious individuals, but at the expense of reduced processing efficiency in anxious subjects. However, as tasks become more demanding and overall load increases, these strategies will become less effective, resulting in reduced performance effectiveness as well as efficiency.

ACT predicts that anxiety will primarily disrupt the inhibition and shifting functions of the central executive and, under stressful conditions, the updating of existing memory representations (Miyake et al., 2000). It further predicts that this will result in a disproportionate degree of stimulus-driven attentional control compared to top-down control and these impairments are consistent with the impact of selective attention and hypervigilance on the orienting and alerting attentional networks described above. Disruption to the inhibition function of the central executive will lead to more attention being directed toward irrelevant or distracting stimuli, whether these are internal, for example worry or worrisome thoughts, or external, for example experimental stimuli. ACT predicts that this disruption will be greater when external stimuli are threat related, but allows that disruption can occur in the absence of external threat (Eysenck et al., 2007). Interference involving the shifting function of the central executive will lead to poor task flexibility and a reduced ability to disengage from one task to complete another. These predictions are supported by a broad range of evidence including eye tracking and neuroimaging studies (Derakshan & Eysenck, 2009).

ACT, as a framework for the effect of anxiety upon attentional control, provides an account of how hypervigilance and selective attention can operate at different times. Prior to the detection of a threat, and in the absence of threat, anxious individuals will be hypervigilant and deploy their attention broadly, facilitating threat detection, but also potentially leading to greater distraction by task-irrelevant stimuli. After a threat is detected, however, attention is selectively narrowed and focussed on threatening stimuli. Importantly, the role of WM in ACT highlights WMC as a target for interventions aimed at reducing the attentional impact of anxiety, suggesting that improvements in WMC would help to reduce the negative effects of anxiety.

1.4 Improving Dynamic Visual Search Performance.

1.4.1 Working memory training. This review has previously discussed some of the roles of WM in visual search and anxiety. Earlier sections touched upon how WMC can predict a range of cognitive abilities, including general intelligence (Engle & Kane, 2004; Kane et al., 2007), and how WMC can moderate the effects of anxiety and related disorders (Eysenck et al., 2007). Given the importance of WM in these respects, it is not surprising that training, aimed at improving WMC, may have a range of benefits that potentially extend to executive function, verbal reasonining and fluid intelligence (Brehmer, Westerberg, & Bäckman, 2012; Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Klingberg, 2012). One common form of WM training is Cogmed (2015), which uses various verbal and visuo-spatial memory span tasks that adapt their difficulty in order to fully tax the ability of the user. A standard regime of Cogmed then requires the user to complete regular sessions of approximately 30 minutes a day, for five days a week, over a period of five weeks. Another common form of training is based around adaptive n-back tasks, such as the dual n-back developed by Jaeggi and colleagues (Jaeggi et al., 2007). This particular form of n-back training uses concurrent auditory and spatial stimulus presentation, and involves regular sessions of approximately 30 minutes a day, every day, over 15 days.

WM training appears to have a range of transferable benefits across variety of populations (Klingberg, 2010). In particular, adaptive dual n-back training has been shown to improve the attentional control of a sample of dysphoric patients relative to an active control group (Max Owens, Koster, & Derakshan, 2013). In a sample of children with social, emotional and behaviour difficulties, Cogmed training was associated with improvements in WMC, as well as teacher reported behavioural and attentional control (Roughan & Hadwin, 2011). Evidence from a child ADHD (attention deficit hyperactivity disorder) sample showed that WM training, including visuo-spatial, digit span and letter span tasks that adaptively increased in difficulty, significantly improved performance not only on the training tasks, but also on an untrained WM task and on Raven's Matrices, a test of non-verbal fluid intelligence (Klingberg, Forssberg, & Westerberg, 2002). Wider transfer of training benefits has been observed following Cogmed training in younger and older adults in the Paced Auditory Serial Addition Test and the Cognitive Failures Questionnaire, which suggests that the training also improved attentional control (Brehmer et al., 2012). Functional magnetic resonance imaging (fMRI) results have shown that training benefits were related to increases in prefrontal and parietal activity, in particular the middle frontal gyrus, which may be related to the broader benefits found in capabilities related to WM (Olesen, Westerberg, & Klingberg, 2004).

WM is regarded by some as a ‘work in progress’. It has been suggested that current training programmes offer only limited benefits and that, in some cases, post-training improvements may represent practice effects (Jaeggi, Buschkuehl, Jonides, & Shah, 2012; Shipstead, Hicks, & Engle, 2012). While this area of research is relatively new, it has been the subject of many publications and, given the publication of null results, there are already many published meta-analyses, reviews and discussions.

One meta-analysis, focussed on Cogmed training, identified nearly 20 studies that either lacked an appropriate control group or had limited data reported on the intervention, transfer measures or rating scale and suggests that future studies need to address key issues of design, including control conditions and random group allocation, and develop a more thorough theoretical account of training transfer (Hulme & Melby-Lervåg, 2012). Indeed, the type of control group has also been a central point of discussion in a number of other recent reviews, given evidence of quantitative differences between studies that use passive (no contact) vs. active (non-adaptive or alternative task) control groups (Au et al., 2014; Dougherty, Hamovitz, & Tidwell, 2015).

Another meta-analysis of 20 studies that used n-back based working memory training concluded that, overall, there was a modest transfer effect of WM training upon tests of fluid intelligence (Au et al., 2014). A number of factors were examined that might moderate this effect. In particular, they found that studies with a passive control reported significantly larger transfer effects than those with an active control. It is suggested that an interaction with location or remuneration may be at least partly responsible for this, as most passively controlled studies took place outside of the United States and actively controlled studies typically compensated individuals to a greater extent (participation may only be monetarily motivated for some individuals). The analytic approach taken in this review did receive criticism and a re-analysis of the data suggested some transfer effects may have been non-significant (Melby-Lervåg & Hulme, 2015a). While the original authors later reaffirmed their original conclusions (Au, Buschkuehl, Duncan, & Jaeggi, 2016), differences between active and passive controls were again a central finding in a later Bayesian meta-analysis, with positive training effects only present in studies with passive controls (Dougherty et al., 2015). Active control groups represent an important part of the design of memory training experiments and are crucial in excluding other sources of variance that may be present in passive control conditions. With regard to control conditions in particular, protocol does appear to vary with location and this serves to emphasise the importance of standardising training regimes for research purposes.

In more recent studies, training protocols and results have continued to vary. A study using a short 10-day programme of Cogmed training found no evidence that training benefits transferred to other categories of WM task, such as an *n*-back, but did find some benefits to performance on visuo-spatial span tasks that more closely resembled the training task (Holmes, Byrne, Gathercole, & Ewbank, 2016). Another study developed a short, six session, training programme based around three different adaptive WM tasks that involved an *n*-back, a WM search task and a WM updating task (Maraver, Bajo, & Gomez-Ariza, 2016). This study found that, relative to controls, training improved performance in an untrained WM task and, in terms of far transfer, an abstract reasoning task and a test of general cognitive flexibility. A recent small scale meta-analysis of four studies, using the same three-session verbal WM training procedure, found significant near-transfer to untrained WM tasks in addition to far-transfer to a measure of fluid intelligence (Borella, Carbone, Pastore, De Beni, & Carretti, 2017). It should be noted, however, that all four studies in this meta-analysis exclusively involved older adults and the generalisability of these findings to younger adults may be limited. Another study used tasks from Lumosity, an online commercial 'brain training' product, as the basis for a 20 to 30-day programme of WM training (Clark, Lawlor-savage, & Goghari, 2017). They found no improvements in terms of near or far-transfer relative to both active and passive controls.

The benefits of effective WM training may extend to visual tasks due to the strong links between WM, attentional control and the role of WMC in moderating the negative effects of conditions like anxiety. WMC has been shown to predict performance in a range of visual search tasks, especially those that require higher levels of top-down control (Kane et al., 2006; Peltier & Becker, 2016, 2017; Sobel, Gerrie, Poole, & Kane, 2007) and this is to be expected given the role of WM in the maintenance, storage and/or transfer of target templates (Drew et al., 2016; Soto, Hodsoll, Rotshtein, & Humphreys, 2008). WM training may be particularly beneficial to performance in a demanding dynamic search task and, for individuals whose performance is impaired by anxiety or intolerance of uncertainty, it may also improve the ability to compensate for these impairments.

1.4.2 Transcranial direct current stimulation. Electrical brain stimulation has a history in animal research, but recently, there has been more interest in the usefulness of non-invasive techniques, particularly tDCS (transcranial direct current stimulation), but also tACS (alternating current) and tRNS (random noise), in human subjects. TDCS typically involves the application of a weak electrical current (1-2mA), via saline soaked sponge electrodes, to the scalp in order to modulate neuronal excitability. This technique can have excitatory effects, via neuronal depolarisation resulting from anodal stimulation, or inhibitory effects, via neuronal hyperpolarisation resulting from cathodal stimulation (Dayan, Censor, Buch, Sandrini, & Cohen, 2013). Stimulation can be applied to many different cortical areas and there is a large body of research on the stimulation of visual and motor areas (e.g., Antal & Paulus, 2008; Antal et al., 2004; Antal, Kincses, Nitsche, & Paulus, 2003; Nitsche & Paulus, 2000; Nitsche & Paulus, 2001; Rosenkranz, Nitsche, Tergau, & Paulus, 2000). This discussion focuses on the stimulation of frontal and prefrontal regions, in particular the dorsolateral prefrontal cortex (DLPFC), and the potential for improvement in WM and attentional control.

In some cases, the differential effects of anodal and cathodal stimulation are not always so clear. For example, differences in ‘neuronal geometry’ can result in mixed results, with both anodal and cathodal stimulation having similar effects on a transcranial magnetic stimulation (tMS) evoked motor response (Nitsche & Paulus, 2000; Rosenkranz, Nitsche, Tergau, & Paulus, 2000). A recent review has also identified difficulties with predicting precise outcomes of tDCS when investigators fail to consider how stimulation may modulate multiple brain functions simultaneously (Tremblay et al., 2014). The outcomes of tDCS can also be influenced by the interhemispheric balance of activity (Fecteau, Knoch, et al., 2007) and the state of the cortex at the time of stimulation, so-called state dependency (Silvanto, Muggleton, & Walsh, 2008). It is noted that while these all represent sources of inter-individual differences in response to tDCS, a recent study found high levels of intra-individual consistency, with the response of any given individual to stimulation remaining constant. (Hsu, Juan, & Tseng, 2016).

Safe parameters for stimulation have been established through animal studies that investigated the neural damage caused by electrical stimulation with a selection of charge densities, over different time periods and with different electrode sizes (Yuen, Agnew, &

Bullara, 1981). While stimulation parameters do vary slightly, most studies use standard montages, with electrode sizes, currents and durations falling with a relatively small range (Dayan et al., 2013; Nitsche et al., 2008) and within these parameters most participants report no side effects more severe than mild tingling or itching (Poreisz, Boros, Antal, & Paulus, 2007). A recent refinement to the more traditional stimulation procedure is high-definition tDCS (HD-tDCS), which involves a more precisely targeted application of electrical current via a central anode surrounded by multiple cathodes in a ring configuration (Gözenman & Berryhill, 2016).

A number of recent meta analyses have identified cognitive benefits associated with tDCS, in particular the effects of stimulation of the DLPFC on WM (Greenlee et al., 2016; Hill, Fitzgerald, & Hoy, 2016; Summers, Kang, & Cauraugh, 2016). Prefrontal tDCS has been shown to be effective in improving WM performance, with anodal stimulation of the left DLPFC significantly improving accuracy on a verbal three-back task relative to several control conditions (Fregni et al., 2005). Other studies have also shown similar results in n-back type tasks (Brunoni & Vanderhasselt, 2014; Nitsche et al., 2008), although sometimes only in terms of response times (Mulquiney, Hoy, Daskalakis, & Fitzgerald, 2011). One study found that the benefits to WM of prefrontal tDCS were restricted to more educated participants and this may be due to an interaction with memory strategy (Berryhill & Jones, 2012). In patient groups with depression and Parkinson's disease, similar broad improvements in a number of WM tasks were found (Boggio et al., 2006; Fregni, Boggio, Nitsche, Rigonatti, & Pascual-Leone, 2006; Oliveira et al., 2013) and, in another study on patients with depression, stimulation improved accuracy on an emotional go/no-go task (Boggio et al., 2007). A number of more recent studies have provided evidence that differentially links stimulation of the left and right DLPFC to verbal and spatial WM processes respectively (Talsma, Kroese, & Slagter, 2017; Trumbo et al., 2016). Further evidence from patient samples links stimulation of the left DLPFC to verbal WM in Huntingdon's Disease (Eddy, Shapiro, Clouter, Hansen, & Rickards, 2017) and dementia patients (André et al., 2016). Other studies have found that a combination of stimulation of the left DLPFC and WM training has improved verbal WM outcomes (Au et al., 2016; Ruf, Fallgatter, & Plewnia, 2017).

Stimulation of the DLPFC appears not only to modulate WM performance, but also a range of other cognitive functions and behaviours. A recent meta-analysis found that stimulation of the DLPFC reliably influenced performance in tasks measuring executive functions (Dedoncker, Brunoni, Baeken, & Vanderhasselt, 2016). This finding is consistent with a recent study which found that stimulation of the left DLPFC specifically benefited the executive control attentional network (Miler, Meron, Baldwin, & Garner, 2017). Stimulation of this region has been shown to influence risk taking behaviour and the balancing of potential reward against the risk of loss (Fecteau, Knoch, et al., 2007; Fecteau, Pascual-Leone, et al., 2007). Cathodal stimulation of the left DLPFC was associated with a significantly lower degree of risk taking compared to controls, consistent with the importance of the DLPFC in risk taking and inhibitory control. Further, a number of studies have also examined the effect of prefrontal tDCS upon performance in applied sustained attention and vigilance tasks (for a review see Parasuraman & McKinley, 2014). In a military threat detection task, where subjects search for concealed threat items, like bombs, in naturalistic dynamic and static scenes, stimulation of the right inferior front gyrus (IFG) improved performance in terms of hit and false alarm rates (Falcone et al., 2012). Similar benefits of prefrontal tDCS were found in a related military visual search task, although prior task experience and previous training were found to be important in benefitting from stimulation (McKinley, McIntire, Bridges, Goodyear, & Weisend, 2013). Stimulation of the left DLPFC has also been shown to improve sustained attention in mock air traffic control task (J. T. Nelson et al., 2014) and to benefit multitasking ability (J. Nelson et al., 2016). In line with previous results, tDCS was found to be associated with an improved ability to discriminate targets.

TDCS offers a non-invasive and relatively fast (certainly in comparison to a programme of WM training) means of improving performance on a variety of memory and attentional tasks in the short term, with no evidence of negative side-effects. The specific effects of tDCS appear to include increased WMC, greater inhibitory control and a reduced vigilance decrement, all of which could be highly beneficial when completing a complex visual search or target detection task.

1.5 Discussion and Summary

This chapter has introduced visual search an important activity in the real-world, and highlighted the gap that exists between the existing literature and the types of dynamic search task that are required in many real-world scenarios. In reviewing the literature on visual search, this chapter has considered prominent models of search and has examined the processes involved in sustaining attention over extended periods of time. A range of factors have been identified that can impact on search performance, in particular, search for multiple targets and varying levels of target prevalence. These effects are well-established, but empirical evidence comes predominantly from static search tasks, and an understanding of the extent to which they hold true for dynamic tasks is presently lacking. This review also identifies sources of individual variation that may be important predictors of performance in dynamic search tasks, specifically anxiety, intolerance of uncertainty and WMC, and, based on these, further suggests two viable means of improving dynamic search performance, specifically WM training and tDCS.

Given the gaps in the existing literature on dynamic search, it is not surprising that there is no standardised dynamic search task that would be the equivalent to ‘T’ and ‘L’ static search tasks. The present thesis therefore introduces a novel dynamic colour search task that will form the basis of the experiments included in all three empirical chapters. The primary goal of the present thesis is to use this task to understand how dynamically changing displays are searched and how this differs from the search of static displays. Chapter 2 addresses this goal, specifically by examining the extent to which dynamic changes can offer predictive pre-cues and facilitate the detection of targets. The second goal of this thesis is to understand how individual differences in anxiety, intolerance of uncertainty and WMC, given their roles as outlined in this review, influence dynamic search performance. This goal is addressed in Chapter 2, but also in Chapter 3, which presents a pair of experiments focused on WM training and tDCS interventions. The experiments in Chapter 3 primarily address the third goal of this thesis, which is understand the extent to which these two interventions influence dynamic search performance. Chapter 4 seeks to extend the basic findings of earlier chapters, in addressing the primary goal of this thesis, by examining the dynamic search of numerical *and* colour stimuli within dual-target conditions. Together, the work presented in the following chapters makes a significant theoretical and practical contribution to the literature on dynamic visual search.

Chapter 2

Individual Differences in Search and Monitoring for Colour Targets in Dynamic Visual Displays

2.a Abstract

Many real-world tasks now involve monitoring visual representations of data that change dynamically over time. Monitoring dynamically changing displays for the onset of targets can be done in two ways: detecting targets directly, post-onset, or predicting their onset from the prior state of distractors. In the present study, participants' eye movements were measured as they monitored arrays of 108 coloured squares whose colours changed systematically over time. Across three experiments, the data show that participants detected the onset of targets both directly and predictively. Experiments 1 and 2 showed that predictive detection was only possible when supported by sequential colour changes that followed a scale ordered in colour space. Experiment 3 included measures of individual differences in working memory capacity (WMC) and anxious affect and a manipulation of target prevalence in the search task. It found that predictive monitoring for targets, and decisions about target onsets, were influenced by interactions between individual differences in verbal and spatial WMC and intolerance of uncertainty, a characteristic that reflects worry about uncertain future events. The results have implications for the selection of individuals tasked with monitoring dynamic visual displays for target onsets.

2.b Publication Note

This chapter is currently in press at the Journal of Experimental Psychology: Applied. Muhl-Richardson, A., Godwin, H. J., Garner, M., Hadwin, J. A.,

Liversedge, S. P., & Donnelly, N. (in press). Individual Differences in Search and Monitoring for Color Targets in Dynamic Visual Displays. *Journal of Experimental Psychology: Applied*.

2.1 Introduction

Monitoring electronic displays for the onset of targets is a key part of many real-world activities and involves sustaining attention over a set of items whose state (or identity) can change (Warm et al., 2015; Warm & Parasuraman, 2008). There will be occasions when changes are minimal and all items remain as distractors requiring observers to take no action. There will also be occasions when some items switch from a distractor to a target state requiring a response to be made. The present set of experiments explores the psychological attributes that support the monitoring for the onset of a target colour amongst an array of items that change colour over the time course of a trial.

To provide a detailed real-world example of this type of scenario, consider the case where the colours of items in a display are coded to reflect the density of geological rock formations in a 3D volume (e.g., Donnelly, Cave, Welland, & Menneer, 2006; see Figure 2.1). In this case, the density of sandstone might be coded as blue, limestone as white, and shale as red. A geologist might sequentially inspect 2D slices of this volume in the hope of finding red in the display, an indicator of hydrocarbon-rich shale deposits. This might be a simple task if displays contained only red, blue and white (i.e., detecting the presence of a red target amongst white and blue distractors). However, variations in density lead to subtle hue and luminance changes being presented and the heterogeneity of colours within the image makes the detection of targets amongst distractors more difficult (Duncan & Humphreys, 1989). The likelihood of overcoming these challenges might be enhanced if, over time, attention could be focused on likely targets rather than distributed across the whole display. For example, this would be so if the appearance of pink in the current slice being inspected might indicate the probable onset of red in a later slice. Of course, similar challenges occur in monitoring changing displays in less benign situations (see also Drew, Võ, & Wolfe, 2013).

There is very little visual search literature to inform our understanding of searching in displays of changing colour items. Much of the evidence from dynamic search tasks involves stimuli that move or change in luminance (e.g., Kunar & Watson, 2011, 2014). A recent study involving a dynamic orientation search task suggests that the additional load associated with organizing and updating representations of objects as they change state can significantly reduce search efficiency (Jardine & Moore, 2015) but it is not clear how this might generalize to colour search. Our starting point and working hypothesis is that initial monitoring for colour targets uses a broad target template (Stroud et al., 2012, 2011) that allows prioritization of possible targets based on similarity to the target. If a distractor is prioritized it can be tested against a more specific target template when it changes colour (e.g., changes from a pink to a deeper red).

The first objective, therefore, is to find and quantify evidence of predictive behaviour in the search for colour targets. This is addressed by recording basic behavioural data (hit rate, false alarm rate and response times) and eye movement data as participants search for the onset of either one or two colour targets during a forty-second presentation of changing colour items. The prediction is that distractors that are close to targets in colour space will be prioritized for monitoring, and that this will be manifest in the eye movement record (i.e., increased fixations to distractors that neighbour targets in colour space relative to other distractors).

The second objective is to test a specific hypothesis in relation to individual differences in predictive monitoring for colour targets. In line with recently suggested guidelines for the study of individual differences in human factors research (Szalma, 2009), a set of relevant characteristics that might impact upon predictive monitoring were determined. Prior research has shown that verbal and spatial working memory capacity (WMC) are associated with various factors important to search (Schwark, Sandry, Macdonald, & Dolgov, 2012; Soto & Humphreys, 2007; Anderson, Mannan, Rees, Sumner, & Kennard, 2008), the ability to sustain attention over extended period of time (Caggiano & Parasuraman, 2004), the maintenance of a task set (Kane, Bleckley, Conway, & Engle, 2001; Mcvay & Kane, 2012), maintaining attentional engagement (Sörqvist & Marsh, 2015, p. 269), flexibility in the allocation of attention (Bleckley, Durso, Crutchfield, Engle, & Khanna, 2003; Fukuda & Vogel, 2011) and the inhibition of return to previously searched locations (Klein, 2000). More recently, it has been shown that visual WMC, attentional control and vigilance ability are particularly important predictors of performance in low prevalence visual search in particular (Peltier & Becker, 2017).

Trait anxiety, and also state anxiety, are known to impact negatively on visual search (review by Richards, Benson, Donnelly, & Hadwin, 2014) and reduce perceptual sensitivity (Pacheco-Unguetti, Acosta, Lupiáñez, Román, & Derakshan, 2012). Theoretical frameworks like Attentional Control Theory (ACT) support the suggestion that the mechanism for this effect is that anxiety reduces the attentional resources (e.g., WMC) available for a given task (Derakshan & Eysenck, 2009; Eysenck & Derakshan, 2011; Eysenck et al., 2007). This leads individuals with elevated anxiety to focus attention on internal (e.g., worrisome thoughts about performance) and/or external threat (e.g., potential negative evaluation from others). While ACT primarily considered trait anxiety, interference with attentional control has been demonstrated in individuals with high state anxiety (Derakshan, Smyth, & Eysenck, 2009). The impact of elevated anxiety on task performance is particularly striking for individuals with low WMC (Eysenck & Derakshan, 2011; Matthew Owens, Stevenson, Hadwin, & Norgate, 2014). The present hypothesis is, therefore, that monitoring for the onset of colour targets will be poor in individuals high in anxiety and low in WMC.

Determining when distractors change to be targets is a decision that comes with a level of uncertainty. Intolerance of uncertainty (IU) is a characteristic that is linked to generalized anxiety (Birrell, Meares, Wilkinson, & Freeston, 2011; Buhr & Dugas, 2006) and individuals who report greater IU are more likely to take steps to avoid uncertainty or ambiguity (Birrell et al., 2011; Carleton, Norton, & Asmundson, 2007). IU has been associated with attentional biases even after factors including anxiety, depression and distress were controlled for (Fergus et al., 2013; Fergus & Carleton, 2016). In the present case, high IU is likely to impact specifically on the criterion used to determine when a distractor has changed to a target. It is predicted that greater symptoms of IU will be associated with a greater likelihood of generating false alarms to distractors that are similar to targets.

The present study utilized behavioural (hit rate, response time and false alarms) and eye movement measures (first fixations to targets, fixation durations, numbers of fixations and scanpath lengths) to examine target detection and monitoring in dynamically changing arrays of colour stimuli. In addition to this, this study set out to test a specific hypothesis in relation to individual differences in order to determine who might perform well in this type of complex visual task. Colour change dynamics were controlled such that stimuli changed according to sequential single-steps through an ordered set of 16 colours, to facilitate the prioritization and monitoring of target-similar distractors with a higher likelihood of becoming become targets. Experiments 1 and 2 included manipulations of these colour change dynamics with a view to determining how and when forthcoming targets were predicted and monitored. Individual differences in WMC and anxious affect were considered in Experiment 3.

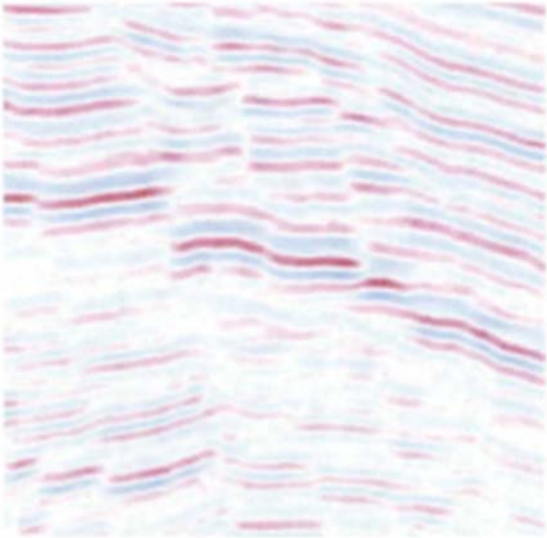

Figure 2.1. Example of a 2D slice taken from a 3D data volume.

2.2 Experiment 1

The goal of Experiment 1 was to provide evidence that target detection in dynamically changing displays is supported by the selective prioritization and monitoring of target-predictive distractors that are similar to targets. Participants searched for colour targets within dynamically changing displays of coloured squares while their eye movements were recorded. Across two experimental conditions the dynamics of colour change were manipulated such that (1) stimuli changed according to sequential single-steps through an ordered set of 16 colours or (2) colour changes were randomized. It was predicted that sequential single-step changes through a psychologically ordered colour space would support a predictive search and monitoring strategy that would not be supported by randomized colour changes and that such a strategy would improve the speed and accuracy of target detection. The difference between conditions should be evident in the eye movements made to targets and distractors whose presence might indicate an emerging target. Eye movement recordings were used to determine when targets and forthcoming targets were first fixated as a function of the number of colour steps from the target colour. By definition, if targets were first fixated at the target colour, this would not indicate predictive monitoring. However, if forthcoming targets were first fixated as target-predictive distractors, operationalized here as one or two steps from the target colour, then this would be consistent with predictive monitoring. In the condition of randomized colour changes, a target onset could follow any of the non-target colours. This meant that no distractor was predictive of target onsets in the randomized colour change condition. In addition to reporting eye movement data, hit and false alarm rates and response times (RTs) are also reported.

2.2.1 Method

2.2.1.1 Design. The independent variable was the type of change (sequential or random) that occurred within the displays and participants completed a block of each condition in counterbalanced order. There were multiple dependent variables. Performance across each experimental condition was recorded in terms of RT, hit rate and false alarm rate. Eye movement recordings were used to determine the proportion of first fixations on targets and forthcoming targets 1 and 2 colour steps from the target colour.

2.2.1.2 Participants. Sixteen undergraduate and postgraduate students (13 females; M_{age} = 24.8 years; *SD* = 5.5; age range: 19-41 years) participated in the study for course credits or compensation of £7.50. All participants had normal visual acuity (at least 1.0 decimal VA at 70 cm), tested using the Freiburg Visual Acuity Test (Bach, 1996), and normal colour vision, tested using the City University Colour Vision Test 3rd Edition (Fletcher, 1998). All experiments in the current paper were approved by the ethics committee of the School of Psychology at the University of Southampton and by the Ministry of Defence Research Ethics Committee. This sample size was chosen to ensure that each of the 16 colours was assigned to at least one participant as a target.

2.2.1.3 Apparatus. Stimuli were displayed on a 21-inch CRT monitor operating at a resolution of 1,024 x 768 pixels and a refresh rate of 120 Hz connected to an SR Research EyeLink 1000 eye-tracker operating at a sampling rate of 1000 Hz. A nine-point calibration procedure was used and calibration was accepted only when none of the points had an error of more than 0.5° of visual angle. Participants were seated 70 cm from the display, the display was viewed binocularly, although only the right eye was tracked, and a chin rest was used to keep participants' heads stable during the experiment. The experiment was programmed using SR Research Experiment Builder, with additional custom code written in Python. Participants responded using a Viglen USB optical mouse.

2.2.1.4 Stimulus spatial properties. Visual angles were calculated from the centre of the display (values vary marginally for more eccentric locations). Individual coloured squares (items), were 0.57° x 0.57°, and displayed in irregular 12 x 9 arrays. Items never abutted, but were randomly 'jittered' within the constraints of an invisible grid, such that each stimulus appeared within an area of 2.15° by 2.15°, which was used to code fixations. The maximum size of the whole array of colour stimuli was 24.78° x 18.36° and 108 items were always present.

2.2.1.5 Stimulus colour properties. Stimuli were coloured using a 16-item colour scale (see Menneer et al., 2007). For each participant, one colour was the target (T) and 15 colours were distractors (D). Of the 108 coloured squares, 96 squares were always at least 3 steps away from being a target and these were considered background distractors. There were 12 squares that were allowed to display colours within 2 colour steps of the target. The locations of these 12 squares were varied across trials and, while unknown to participants, these were never located at the edge of the array or immediately adjacent another of these 12 squares. The target colour was varied and counterbalanced between participants, such that each colour was the target for one participant (Figure 2.2 shows the full colour scale).

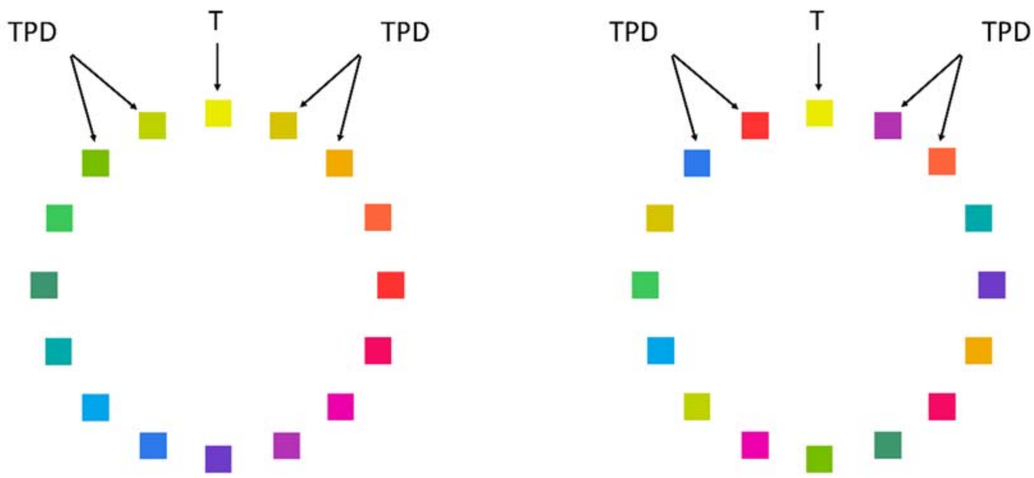

Figure 2.2. Ordered colour scale (left) and an example of a shuffled colour scale (right; used in Experiment 2 only) showing example of what were classed target-predictive distractors (TPDs) when the target (T) was the indicated colour.

2.2.1.6 Stimulus dynamic properties. Stimulus arrays were updated with a variable refresh rate, this resulted in displays that refreshed at a mean rate of once every 107 ms (*SD* = 100) and the mean rate of colour change for each item was a change every 336 ms (*SD* = 342). Background distractors in both conditions could change between the 11 colours that were at least 3 steps from the target colour. When changing colour, items could change to be closer to, or further from, the target colour. For background distractors, these two possibilities were equally likely, other than when three steps from the target colour. At certain time points during trials, the 12 squares that could display colours within 2 steps of the target were allowed to change across the full range of 16 colours (or 15 colours if they were not to become a target). This was the case in both the ordered and randomized conditions. As there were up to two targets per trial, at least 10 of these 12 stimuli reached a colour one step from the target, but never achieved a target state. The effect of these conditions was to allow stimuli in the ordered condition to systematically approach the target colour, allowing the colour of distractors to be used as a predictive cue to the onset of targets. Colour could not be used as a cue to predict the onset of targets in the randomized condition.

Each of these 12 items was given a number of key properties, all independently and pseudo-randomly generated within Python: (1) a time at which they were allowed to move within two colours of the target; (2) a time after which they will become a target or a distractor colour one step from the target; and (3) a duration for which they remain present as target or a distractor one step from the target before reverting to background distractor (if no response was made). These values corresponded to the first item starting to move towards a target state after an average of 3,550 ms (*SD* = 1,915), the first target onset after an average of 14,886 ms (*SD* = 1,569), the second target onset (where applicable) after an average of 18,845 ms (*SD* = 2,480). This also resulted in an average duration of targets, if no response was made, of 2,549 ms (*SD* = 1,768). The parameters that controlled stimulus behaviour were selected after piloting to allow for: (1) the possibility of target detection and prediction without excessive difficulty; (2) to ensure that no item could start to approach a target state immediately following the start, or immediately before the end, of a trial; and (3) to allow for inter-trial variation. Responding target-present (irrespective of whether it was a hit or a false alarm) also caused it to reset to a background distractor. While up to two targets might be presented over the course of a trial, only one target could be present at any given time. While colour changes were more salient in the randomized than ordered condition, the relative salience of changes from distractor-to-target and distractor-to-distractor were matched across conditions. A video of a sample trial is included as supplementary material (see Appendix A).

2.2.1.7 Procedure. Participants were first tested for normal visual acuity and colour vision. Participants were shown a static sample of the search display (see Figure 2.3). They were instructed to search for a target square defined by a particular colour, which was shown before every trial, and that responses were to be made as quickly as possible by clicking the mouse cursor on the target. Participants were told that trials might contain no targets, a single target or more than one target, but that only one target would appear at a time. Trials began with a 1 s reminder of the target colour, followed by a 1 s fixation point and each trial lasted 40 s (see Figure 2.4 for the trial sequence). Audio feedback indicating either ‘correct’ or ‘incorrect’ was given for every response. Participants were given a self-paced break halfway through each block of 40 trials. Participants completed two blocks of trials, one each for the ordered and randomized conditions. These were order counterbalanced to preclude any block order effects. In the ordered condition, all colour changes occurred in single sequential steps through the 16 possible colours and stimuli never changed in colour by more than a single step. In the randomized condition items were controlled in the same way but any colour change could be between 1 and 8 steps. In both blocks, 10 out of 40 trials had a single target present and 10 out of 40 trials had two targets present. A practice block of three trials, with sequential colour change dynamics, was given before beginning the first block.

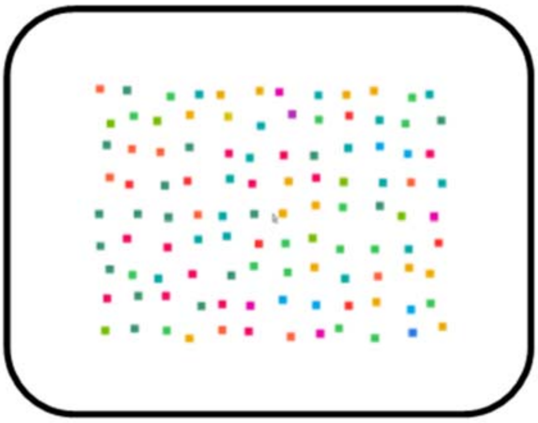

Figure 2.3. An example stimulus display with no targets or target predictive distractors present.

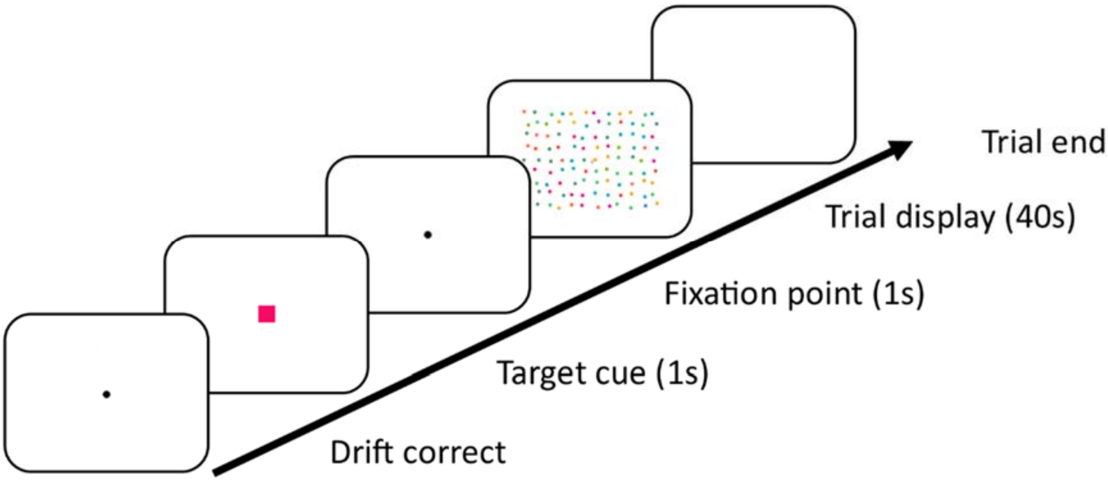

Figure 2.4. Trial sequence with timings (from the start to end of a single trial).

2.2.2 Results

RT exclusion criteria were set *a priori* at above 10,000 ms and below 200 ms from target onset but no responses were outside of these limits. RTs were log transformed before being analysed and untransformed means are also reported. In the eye movement data, fixations were excluded from duration analysis if they were longer than 1,200 ms, shorter than 80 ms in duration or if they corresponded with a manual response (3.98% of all fixations). Proportional data were arcsine square root transformed before being analysed and untransformed means are also reported. Hit rate was defined as the proportion of targets across all trials that were responded to correctly. False alarm rate was defined as the proportion of all responses that were made to non-target stimuli[1].

2.2.2.1 Behavioural performance. For descriptive statistics of the hit rate, RT and false alarm rate see Table 2.1. Contrary to predictions, performance did not differ between ordered and randomized conditions in terms of hit rate, $t(15) = 0.96$, $p = 0.35$, RT, $t(15) = 0.65$, $p = 0.53$, or false alarm rate, $t(15) = 0.20$, $p = 0.84$.

As a baseline check for SOS errors, hit rate and RT to first and second targets in the ordered condition were compared. No significant difference was observed for either hit rate, $t(15) = 1.46$, $p = 0.17$, or RT, $t(15) = 0.11$, $p = 0.91$.

Table 2.1

Mean Hit Rate, Response Time (RT) and False Alarm Rate in Experiments 1, 2 and 3

	Experiment 1		Experiment 2		Experiment 3	
	Ordered	Random	Ordered	Shuffled	Low Prevalence	High Prevalence
Hit Rate	0.86 (0.09)	0.82 (0.12)	0.89 (0.08)	0.61 (0.15)	0.95 (0.12)	0.92 (0.06)
RT (ms)	2,595 (436)	2,451 (682)	2,582 (569)	3,718 (703)	3,098 (1,206)	2,654 (557)
False Alarm Rate	0.19 (0.24)	0.18 (0.18)	0.19 (0.24)	0.24 (0.28)	0.47 (0.35)	0.13 (0.16)

Note. Standard deviations shown in parentheses

[1] Signal detection theory (SDT) measures of sensitivity or response criterion are not calculated due to the non-standard calculation of false alarm rate and, given the dynamically changing nature of the displays, there is no clear determination of what should constitute a correct rejection.

2.2.2.2 Target prediction. To examine target prediction, first fixations to targets and forthcoming targets were analysed in the ordered condition. In the randomized condition first fixations to targets and forthcoming targets in a distractor state one or two steps from becoming a target were analysed (see Figure 2.5). Only first fixations to forthcoming targets that went on to receive a response are included. First fixations give a measure of the state of items when they initially attracted attention. These data were analysed in a 2 (display type: ordered and randomized) x 3 (colour step: T, T+/-1, T+/-2) repeated-measures ANOVA.

As a difference in the ability to predict target onset was expected between display types, it is the interaction between colour steps and display type that addresses our first research question. Colour step and display type interacted, $F(2,30) = 26.62$, $p < .001$, $\eta^2_G = 0.37$. Pairwise comparisons of display type at each number of colour steps from the target revealed no difference between display types for fixations to targets, $t(15) = 1.81$, $p = 0.09$, but a significant difference for fixations to distractors at one step, $t(15) = 8.19$, $p < .001$ and two steps, $t(15) = 2.33$, $p = .03$. The analysis revealed evidence of targets being first fixated when targets in both ordered and randomized displays and of predictive fixations in ordered displays only. The ability to make predictive fixations to forthcoming targets, in ordered displays, makes these distractors predictive of targets and, henceforth, they are referred to as target-predictive distractors (TPDs).

In addition, analysis of fixations and refixations (an index of monitoring over time) to targets and TPDs in the ordered condition only showed a mean of 2.87 (*SD* = 2.14) total fixations to items first fixated as targets, and 2.26 (*SD* = 1.55) and 1.46 (*SD* = 0.51) total fixations to TPDs first fixated one and two steps respectively from the target. Fixations to background distractors in the ordered condition accounted for an average of 31.52% (*SD* =

7.25) of all fixations made across all participants and each background distractor was fixated on average 0.88 times (*SD* = 1.34).

The effect of predicting forthcoming targets was explored with respect to hit rate, RT and false alarm rate for targets first fixated at T and those first fixated as TPDs at T +/-1 (these data are shown in Figure 2.6 for all experiments). There were too few data to allow meaningful analysis of predicting forthcoming targets at T+/-2 steps. This analysis revealed that predicting upcoming targets: (1) reduced the hit rate for targets first fixated as TPDs one step from becoming a target (*M* = 0.81, *SD* = 0.16) relative to first fixating targets (*M* = 0.93, *SD* = 0.07), $t(15) = 2.71$, $p = .02$; (2) did not speed RT for those items first fixated as a TPD one step from becoming a target (*M* = 2,539 ms, *SD* = 659) compared to when first fixating a target itself (*M* = 2,740 ms, *SD* = 557), $t(15) = 1.29$, $p = .22$.; and (3) led to a false alarm rate for targets first fixated as TPDs one step from becoming targets (*M* = 0.27, *SD* = 0.30) that was significantly greater than zero, $t(15) = 3.64$, $p = .002$.

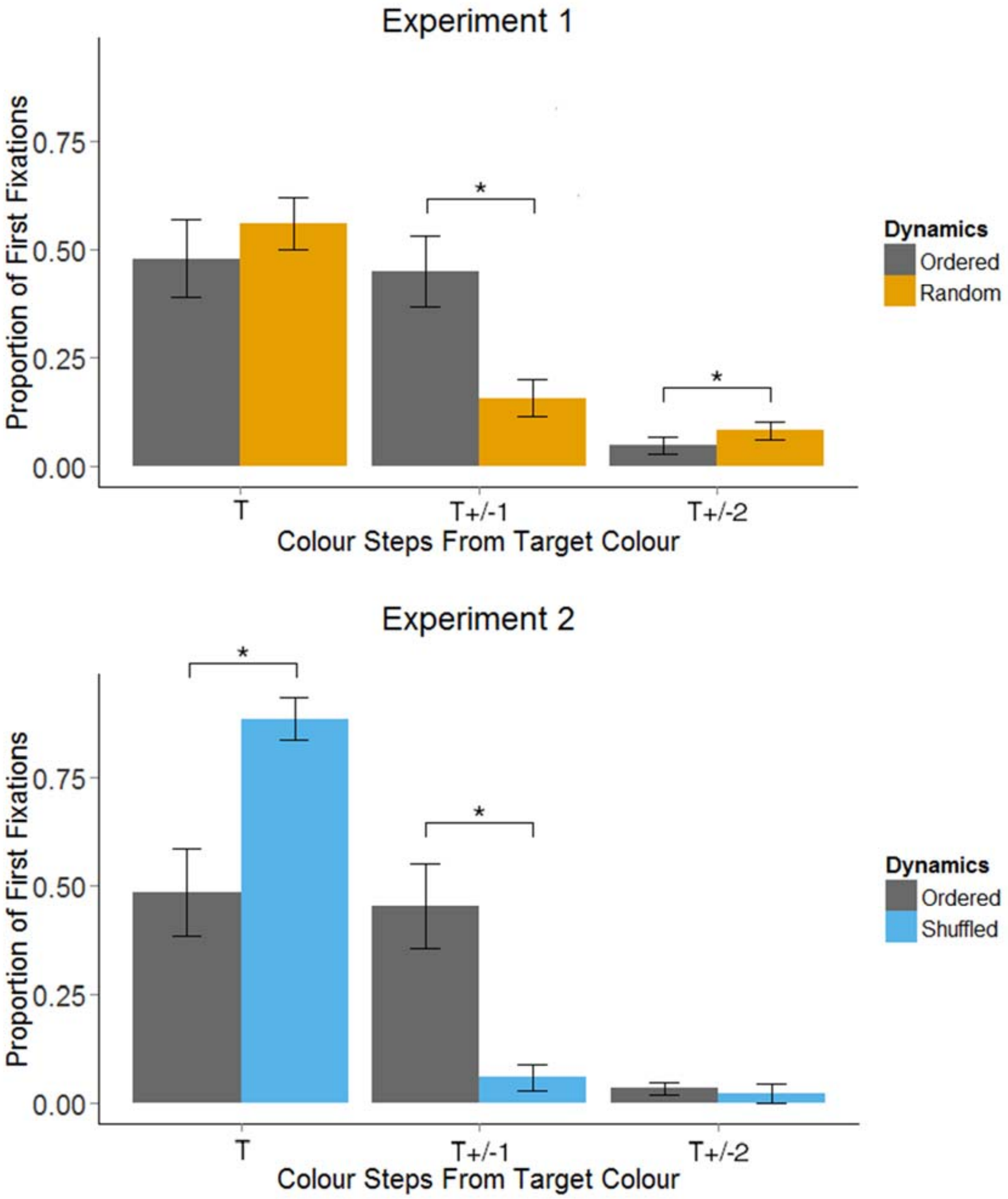

Figure 2.5. The proportion of first fixations to active targets and forthcoming targets as a function of the number of colour steps from the target colour under ordered sequential, randomized and shuffled display dynamics in Experiments 1 (top) and 2 (bottom). Error bars show 95% CIs and '*' indicates a pairwise comparison where $p < .05$.

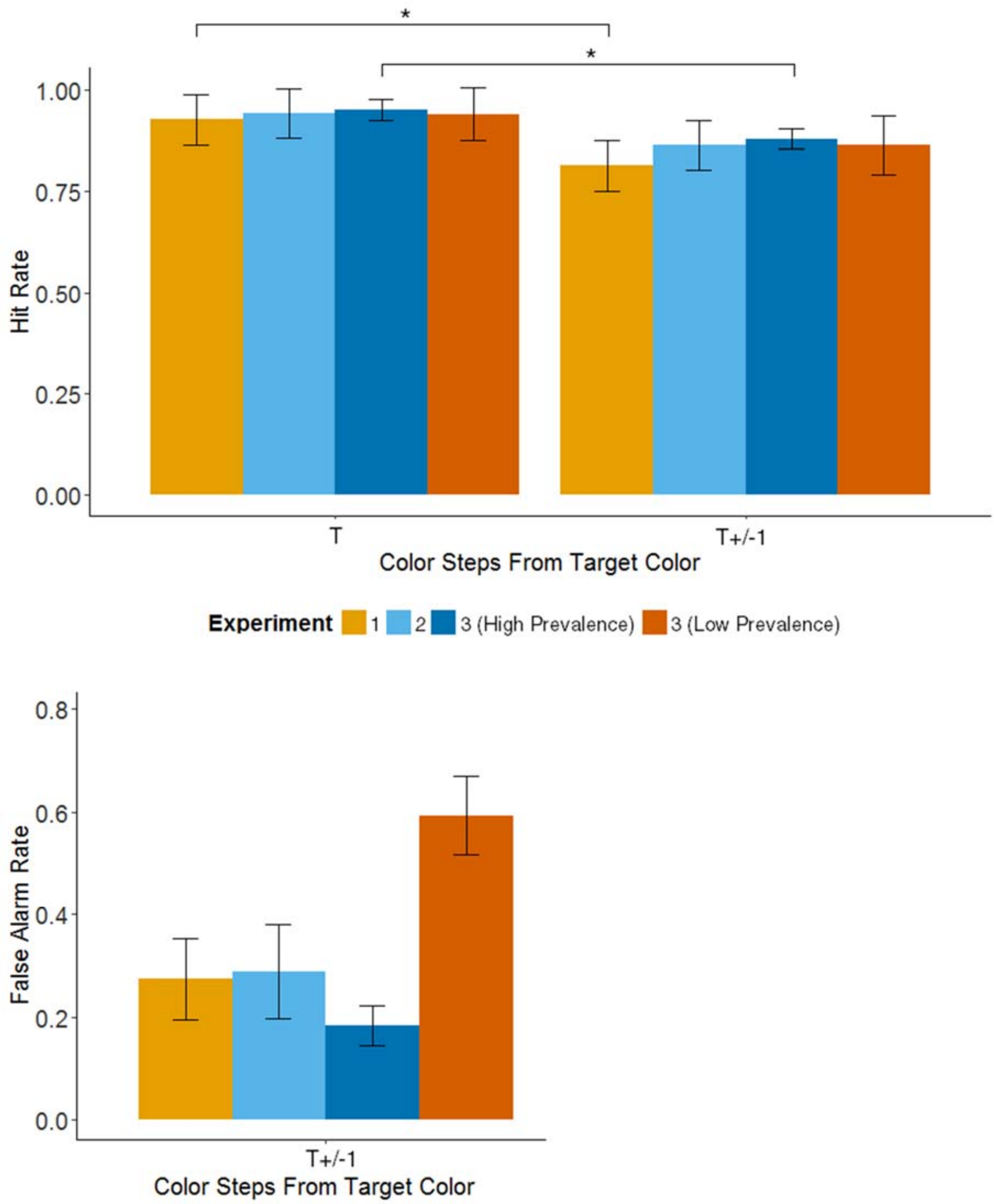

Figure 2.6. The hit rates for targets first fixated as targets and as target-predictive distractors at T+/-1 colour step (top) and the false alarm rates for forthcoming targets first fixated as target-predictive distractors at T+/-1 colour step (bottom) across Experiments 1, 2 and both prevalence levels in Experiment 3. Error bars show 95% CIs and '*' indicates a pairwise comparison where $p < .05$.

2.2.3 Discussion

Experiment 1 found no evidence of the predicted benefit to hit rate or RT of presenting colours in an ordered versus a randomized sequence. These results suggest that the salience of colour change in ordered and randomized conditions did not impact overall performance. However, Experiment 1 demonstrated that single step colour changes enabled the prediction of forthcoming targets via the fixation of TPDs close to targets in colour space in the ordered condition. In the ordered condition, first fixations were as likely to be made to distractors one step from the target colour as to targets themselves. While it was predicted that first fixating TPDs one step from being a target would benefit target detection overall, results were consistent with reduced target sensitivity. For those items first fixated as TPDs, hit rates were reduced relative to when items were first fixated as targets and false alarms were significantly greater than zero.

The results were consistent with an account whereby participants used a broad target template to locate targets or target-similar stimuli one step either side of the target colour, though there was no evidence that using a broadened template actually improved task performance overall. The reason for this is simple. False alarms occurred on roughly one quarter of occasions when fixating distractors that were close in colour to targets. Although participants were monitoring distractors that could soon become targets, the mechanism of prediction was problematic. In some cases, this led to false alarms, where premature responses were made to TPDs before they could become targets. In other cases, this led to misses, where TPDs were fixated and discounted as possible targets. In the context of equivalent overall performance in the randomized and ordered conditions, the existence of these sources of error in relation must imply that more potential targets were being identified in the ordered than randomized condition.

Evidence of uncertainty in relation to detecting targets was found in the analysis of refixations. Refixations were more common when items were first fixated when in the target state and declined monotonically with distance from the target. First fixating a target when in a target state appeared to lead to checking and, in contrast, first fixating a target as a TPD led to sustained attention, reduced checking and an increased false alarm rate. In other words, the tendency to false alarm led to a failure to find evidence of an overall benefit on hit rate of monitoring for target onsets in Experiment 1.

Experiment 2 explored a potential alternative account of the effects of order colour change dynamics found in Experiment 1. It is possible that predictive monitoring for targets in dynamically changing colour displays does not rely on use of an ordered colour space but rather on any predictable pattern of change between colour, for example, if a red distractor always preceded a blue target then this association might be learned and influence search. In the real-world, colour scales used in a variety of imaging and mapping tasks can be defined by the user, for example, in choropleth maps. This might result in arbitrary colour coding that follows a fixed pattern, but does not involve a psychologically ordered colour space.

2.3 Experiment 2

Participants completed the same task as in Experiment 1, with a change in the manipulation of display ordering. The block of the task with randomized colour changes was replaced with a block where colour changes occurred in a predictable pattern but through a shuffled colour space and target-predictive distractors were not target-similar colours. As in Experiment 1, it was predicted that colour changes according to an ordered colour space would support a predictive search strategy. However, when stimuli changed according to a shuffled colour space, it was predicted that the use of a predictive strategy would be very limited due to the requirement to learn colour associations. As before, the extent to which participants are able to engage in predictive target detection will be reflected in the proportion of first fixations to TPDs, with more first fixations to TPDs indicating greater predictive detection.

2.3.1 Method

The method, including the design, apparatus, stimuli and procedure, was the same as for Experiment 1 except for the differences below.

2.3.1.1 Participants. 16 undergraduate and postgraduate students (15 female; M_{age} = 21.6 years; *SD* = 5.7; age range: 18-38 years) participated in Experiment 2. This sample size was chosen to ensure that each of the 16 colours was assigned to at least one participant as a target.

2.3.1.2 Stimulus dynamic properties. Display dynamics were manipulated by generating a pseudo-randomly shuffled (constrained to maintain discontinuity in colour space) colour change sequence for each participant, using the same 16 colours as in Experiment 1 (see Figure 2.2 for an example). While colour changes were more salient in the shuffled than ordered condition, the relative salience of changes from distractor-to-target and distractor-to-distractor were matched across conditions. Each participant completed a block of the task under these conditions and a block under the ordered conditions described in Experiment 1 (these were order counterbalanced).

2.3.2 Results

The data were analysed as in Experiment 1 and, using the same exclusion criteria, 0.31% of all RTs and 3.52% of all fixations were removed before behavioural and eye movement analyses.

2.3.2.1 Behavioural performance. Hit rate was higher, $t(15) = 8.13$, $p < .001$, and RT was faster, $t(15) = 7.87$, $p < .001$, in the ordered condition compared to the shuffled.

False alarm rate did not differ significantly between conditions, $t(15) = 1.13$, $p = 0.28$ (see Table 2.1).

2.3.2.2 Target prediction. With respect to first fixations to targets, the eye movement data revealed a significant main effect of colour step, $F(2,30) = 287$, $p < .001$, $\eta^2_G = 0.84$. As in Experiment 1, where a difference in target prediction was expected between display types, it is the interaction between colour step and display type that is of interest. Colour step and display type interacted, $F(2,30) = 36.06$, $p < .001$, $\eta^2_G = 0.62$, (see Figure 2.5). Pairwise comparisons of display type at each colour step revealed that a greater proportion of first fixations were made to targets in shuffled compared to ordered displays, $t(15) = 5.73$, $p < .001$. A greater proportion of first fixations was made to distractors one step from the target in ordered than shuffled displays, $t(15) = 7.10$, $p < .001$ (see Figure 2.5) and there was a non-significant difference in first fixations made to distractors two steps from the target colour, $t(15) = 1.99$, $p = .06$. The analysis shows a much greater reliance on first fixating targets in the shuffled than ordered condition and replicates the results found in Experiment 1 for the ordered condition, in particular, fixations were made to TPDs in the ordered condition.

Analysis of fixations and refixations to targets and TPDs in the ordered condition showed a mean of 2.71 (*SD* = 1.94) total fixations to targets, and 2.04 (*SD* = 1.35) and 1.58 (*SD* = 1.17) total fixations to TPDs one and two steps from the target respectively. Fixations to background distractors in the ordered condition accounted for an average of 31.03% (*SD* = 6.60) of all fixations made across all participants and each background distractor was fixated on average 0.87 times (*SD* = 1.26).

The same approach was taken as in Experiment 1 with regard to examining the influence of predicting forthcoming targets on behavioural measures. Experiment 2 confirmed the pattern of behavioural data reported in Experiment 1. In the ordered condition of Experiment 2: (1) hit rate was marginally lower when first fixating a TPD one step from becoming a target ($M = 0.86$ $SD = 0.16$) than when first fixating the target itself ($M = 0.94$ $SD = 0.07$), but this effect did not reach significance, $t(15) = 1.91$, $p = .08$ (despite the difference in SD, a Brown-Forsythe test confirmed equality of variance in these data); (2) there was no difference in RTs to targets first fixated as TPDs one step from becoming a target ($M = 2{,}677$ ms, $SD = 961$) and those first fixated as targets ($M = 2{,}500$ ms, $SD = 553$), $t(15) = 0.70$, $p = .49$; and (3) the false alarm rate for targets first fixated one step away from the target colour ($M = 0.29$, $SD = 0.30$) was significantly greater than zero, $t(15) = 3.86$, $p = .002$.

2.3.3 Discussion

The results from the ordered condition of Experiment 2 replicate those from Experiment 1. Overall performance was similar across the two studies. Target detection occurred following direct fixation of targets, as well as the monitoring of target-predictive distractors. The monitoring of target-predictive distractors led to false alarms and a marginally reduced hit rate. The number of fixations to targets also reduced monotonically across targets and TPDs with distance from target. The data are consistent with an error prone predictive monitoring process for upcoming targets.

With respect to displays in the shuffled condition, participants found target detection very challenging and overall performance was less accurate and slower than in the ordered condition. This might be partially accounted for by the increased salience of colour changes in the shuffled than ordered condition, although this is unlikely given the results of Experiment 1 and the high salience of colour changes within the randomized condition. The striking difference between performance in the randomized condition of Experiment 1 and the shuffled condition of Experiment 2 is important. This result suggests that participants were able to ignore randomized colour changes in their search for the onset of a colour target, however, they found it very difficult to ignore systematic colour changes to distractors where changes were not drawn from a psychologically ordered colour space. In other words, systematic changes made outside of a psychologically ordered colour space interfered with the detection of targets.

There was no evidence of predictive target detection in the shuffled condition, as target present responses almost exclusively followed first fixations to targets, and participants showed much longer RTs to targets. Together these data suggest that it was hard for participants to learn the colour associations necessary to make use of TPDs in this condition. Whether participants noticed the shuffled colour sequences was not recorded as part of the formal debriefing, however, no participants indicated that they were aware of a pattern of colour changes in the shuffled condition. Informally, many participants indicated that they found target detection particularly difficult in the shuffled condition, which was consistent with behavioural performance.

Together, it is suggested that Experiments 1 and 2 are consistent with participants using a broad target template to guide search to facilitate predictive monitoring for targets stimuli (Hout & Goldinger, 2015; Stroud et al., 2012, 2011). This is only possible when stimuli change colour according to an ordered colour scale and the template is both broad and narrow enough, to guide search to a colour range that includes the target and TPDs. Importantly, for accurate target detection the use of this broad template must be followed by a separate perceptual decision, based on a more specific template. This second decision involves a more precise target specification but the data suggest that this may be a challenging and error prone process, as this would account for the lowered hit and raised false alarm rates found to targets first fixated as target-predictive distractors relative to those first fixated as targets.

Determining those individuals likely to make such errors in predictive monitoring tasks is a question of significant theoretical and practical significance. Experiment 3 aimed to extend the findings of Experiments 1 and 2 to investigate individual differences that might be associated with errors in this type of monitoring task.

2.4 Experiment 3

Experiments 1 and 2 found evidence that participants engaged in predictive monitoring for targets in arrays of changing colour items. One suggested mechanism that would support such predictive monitoring is the use of a broad target template to first identify items broadly similar to targets, followed by a decision made with respect to a more specific template. Engaging in predictive monitoring in changing displays may be dependent on a number of individual factors. Experiment 3 examined whether predictive monitoring is associated with individual differences in WMC and self-reported trait and state anxiety and IU.

Only ordered displays were used in Experiment 3 and, to increase task difficulty, a manipulation of target prevalence was added. To ensure that the effect of individual differences could be assessed at both low and high prevalence levels, target prevalence was manipulated within participants. This introduces the possibility of carry-over effects between blocks of different prevalence levels as individuals adjust their response criterion to meet the changed task parameters (Vickers & Leary, 1983). However, the feedback provided in the present task should speed this adjustment (Wolfe et al., 2007) and order counterbalancing ensured that any remaining carry-over effects are distributed equally between groups. Consistent with established effects of low prevalence in visual search (e.g., Godwin, Menneer, et al., 2014), it was hypothesized that reduced target prevalence would lower the number of first fixations to targets and the hit rate and increase RTs and the false alarm rate. Moreover, as low prevalence increases uncertainty, it was expected that prevalence would interact with anxiety and IU, such that the effects of low prevalence would be most evidence in individuals with symptoms of anxiety and IU (and low WMC). Additional eye movement measures of the number of fixations, fixation duration and scanpath length are included to further determine the effects of these individual differences upon monitoring behaviour.

2.4.1 Method

The method was the same as for Experiment 1 except for the differences noted below.

2.4.1.2 Design. Target prevalence had two levels, high (66%) and low (5.6%), and was manipulated within participants, such that all participants completed one block at each level of prevalence and these were order counterbalanced.

2.4.1.3 Participants. 33 undergraduate and postgraduate students participated in the study (23 female; M_{age} = 23.9 years; *SD* = 5.7; age range: 18-36 years). Participants completed the study for course credit or were compensated for their time at a rate of £6 per hour. This sample size was chosen to ensure that each of the 16 colours was assigned to at least two participants as a target.

2.4.1.4 Working memory capacity. WMC was measured using spatial and verbal 3-back working memory tasks which were identical in appearance and means of response (Shackman et al., 2006). The spatial task required remembering locations and the verbal task required remembering a letter and, in each case, there were six possible locations or letters that could appear. Trials lasted 500 ms and there was a 2,500 ms interval between trials. The task was continuous and every trial required a response to indicate either a match or non-match with the stimulus presented three trials previously. No feedback was given and the task proceeded automatically if no response was made.

2.4.1.5 Trait and state anxiety. The Spielberger State-Trait Anxiety Inventory Form Y (STAI; Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983) consists of two 20-item self-report measures of anxiety for adults. The two scales, one measuring state anxiety and the other trait anxiety, provide separate scores and each response is made on a four-point scale, generating a total score from 20 to 80 for each. In the current study the reliability of both scales was acceptable ($\alpha > .77$). Approximately 30.3% of the present sample reported elevated scores (i.e., total scores > 40) on the STAI trait scale (Lam, Michalak, & Swinson, 2006).

2.4.1.6 Intolerance of uncertainty. The Intolerance of Uncertainty Short Form (IUS-12; Carleton et al., 2007) is a 12-item self-report measure that assesses reactions to uncertainty, ambiguous situations and future events. It consists of two factors, the first, prospective IU, relates to worry regarding future events and is assessed by 7 items, for example, “I can’t stand being taken by surprise.” The second, inhibitory IU, relates to the extent to which uncertainty might inhibit action or experience and is assessed by 5 items assessing, for example, “when it’s time to act, uncertainty paralyses me.” Each response is made on a five-point scale which ranges from 1 “not at all characteristic of me” to 5 “entirely characteristic of me” and this results in a total score between 12 and 60. In the current study the reliability of the scale was excellent ($\alpha > .92$).

2.4.1.7 Apparatus and materials. The STAI and the IUS-12 were administered using paper questionnaires and the working memory tests were administered on the same computer as the main experiment (see Experiment 1).

2.4.1.8 Procedure. Participants completed the STAI and IUS-12, followed by the spatial and verbal 3-back working memory tasks. The state component of the STAI was completed a further three times: immediately before the search task, between blocks of the search task and at the end of the session. Participants completed two 72-trial blocks of the search task, one at high target prevalence and one at low prevalence, and were given no instructions or information regarding target prevalence levels. In low prevalence blocks, 2 out of 72 trials had a single target present and 2 out of 72 trials had two targets present, such that 4 out of 72 trials (5.6%) had a target present. In high prevalence blocks, 24 out of 72 trials had a single target present and 24 out of 72 trials had two targets present, such that 48 out of 72 trials (66%) had a target present.

2.4.2 Results

The 3-back task data from three participants was incomplete and was not included analysis of WMC. Preliminary analysis of eye movements from the low prevalence condition showed that, given the low number of targets, some participants did not fixate targets as TPDs and therefore did not contribute to analysis of these data. Two approaches were taken in data analysis, with the relevant data being analysed as in Experiments 1 and 2 and the individual differences data being analysed using linear mixed models (LMMs).

2.4.2.1 Behavioural responses. The behavioural data, including hit rate, RT, false alarm rate and first fixations to Ts/TPDs, were analysed as in Experiments 1 and 2. The only difference being that the ‘display type’ factor was replaced with ‘prevalence’ (with two levels, high and low).

Hit rate did not differ significantly between prevalence levels, $t(32) = 0.20$, $p = .84$. RT was faster, $t(15) = 2.57$, $p = .02$, and false alarm rate was lower, $t(15) = 6.51$, $p < .001$, at high target prevalence compared to low (see Table 2.1).

2.4.2.2 Target prediction. With respect to predictive monitoring, there was a significant main effect of colour step, $F(2,64) = 60.91$, $p < .001$, $\eta^2_G = 0.54$, demonstrating that first fixations to TPDs one step from becoming targets were higher than TPDs two steps from becoming targets (see Figure 2.7). In addition, there was a significant interaction between colour step and target prevalence, $F(2,64) = 3.99$, $p = 0.02$, $\eta^2_G = 0.04$). In the low prevalence conditions first fixations fell monotonically from targets through to distractors two steps from becoming targets. In the high prevalence conditions, numerically more targets were first fixated when TPDs one step from becoming targets then when targets themselves. However, pairwise comparisons across prevalence levels revealed no significant differences in first fixations to targets, $t(32) = 1.73$, $p = 0.09$, or TPDs one step from becoming a target, $t(32)= 1.21$, $p = 0.24$, and so the interaction between when first fixations were made to targets and prevalence will not be considered any further.

Analysis of fixations and refixations to targets and TPDs at high prevalence showed a mean of 2.53 (*SD* = 0.43) total fixations to targets, and 2.01 (*SD* = 0.28) and 1.63 (*SD* = 0.42) total fixations to TPDs one and two steps from the target respectively. At low prevalence, there was a mean of 2.73 (*SD* = 1.11) total fixations to targets, and 1.92 (*SD* = 0.68) and 1.64 (*SD* = 0.92) total fixations to TPDs one and two steps from the target respectively. Fixations to background distractors across both prevalence conditions accounted for an average of 31.48% (*SD* = 7.27) of all fixations made across all participants and background distractors that received fixations were fixated on average 0.82 times (*SD* = 1.31).

Next the effects of predictive monitoring on hit rate, RTs and false alarm rate, as in Experiments 1 and 2, are reported, but with a distinction between high and low prevalence conditions. The same approach was taken as in Experiment 1 with regard to examining the influence of predicting forthcoming targets on behavioural measures. At low prevalence: (1) hit rate was not significantly lower when first fixating a TPD one step from becoming a target (*M* = 0.86, *SD* = 0.28) than when first fixating the target itself (*M* = 0.94, *SD* = 0.15), *t*(28) = 1.27, *p* = .22; (2) RT was not significantly different when first fixating a TPD one step from becoming a target (*M* = 3,124 ms, *SD* = 2,505) than when first fixating the target itself (*M* = 3,138 ms, *SD* = 1,426), *t*(26) = 0.81, *p* = .42; and (3) the false alarm rate for targets first fixated as TPDs one step from becoming a target (*M* = 0.59, *SD* = 0.40) was significantly greater than zero, *t*(32) = 8.56, *p* < .001.

At high prevalence: (1) hit rate was significantly lower when first fixating a TPD one step from becoming a target (*M* = 0.88, *SD* = 0.11) than when first fixating the target itself (*M* = 0.95, *SD* = 0.06), *t*(32) = 3.97, *p* < .001; (2) RT was not significantly lower when first fixating a TPD one step from becoming a target (*M* = 2,604 ms, *SD* = 622) than when first fixating the target itself (*M* = 2,692 ms, *SD* = 614), *t*(32) = 0.88, *p* = .38; and (3) the false alarm rate to targets first fixated as TPDs one step from becoming a target (*M* = 0.18, *SD* = 0.22) was significantly greater than zero, *t*(32) = 4.76, *p* < .001. Overall, these experimental data from Experiment 3 confirm the findings from Experiments 1 and 2.

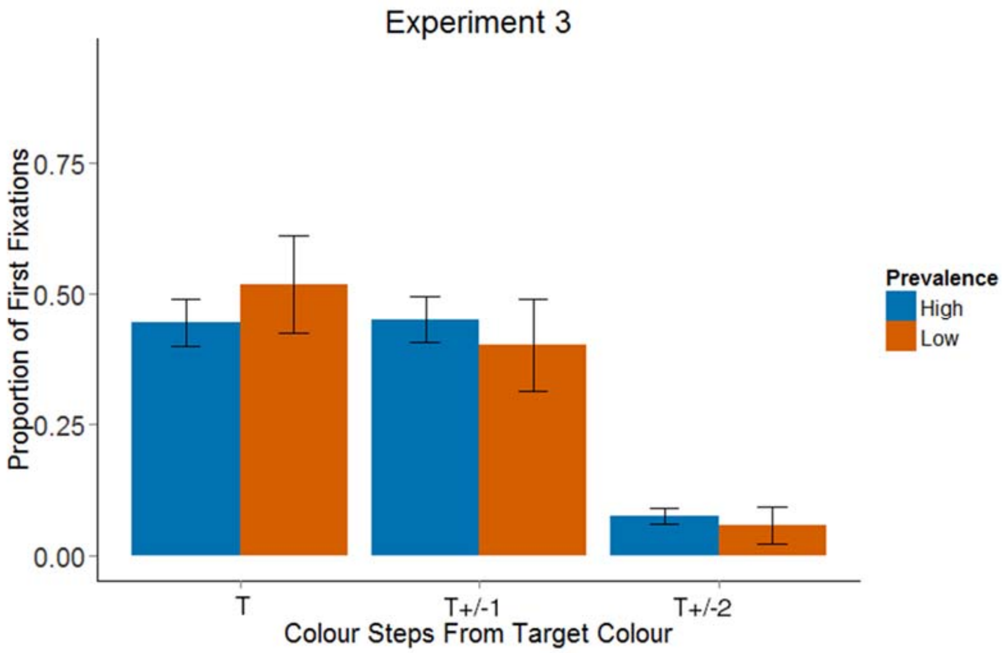

Figure 2.7. The proportion of first fixations to targets and forthcoming targets as a function of the number of colour steps from the target colour under high and low target prevalence in Experiment 3 (error bars show 95% CIs).

2.4.2.3 Individual differences. LMM analyses were performed in R (v3.0.3) using the lme4 package (v1.1-7; Bates, Mächler, Bolker, & Walker, 2014). These models allow analysis of these data and the interactions among the variables as continuous variables and, because they do not rely upon aggregated means, are more robust to missing data, outliers and unbalanced cell counts. All models included participant as a random factor and, in all cases, model fitting began with a model containing the full set of two-way interactions and iterated through different variants until reaching the best-fitting model (any models that failed to converge were excluded). The effects of individual differences in spatial WMC, verbal WMC, trait anxiety, state anxiety and IU were considered in relation to a number of behavioural and eye movement measures. RT, fixation duration, number of fixations per trial and scanpath length and an index of the extent predictive fixations to TPDs were all analysed using standard LMMs. Hit rate and false alarm rate were analysed using binomial generalized linear mixed models (GLMMs). In the case of the analysis of hit rate, every target was entered into the model as a binary value indicating whether or not that target received a hit. Similarly, for the analysis of false alarm rate, every response was entered into the model as a binary value indicating whether or not that response was a false alarm. In addition to the robustness of these models, this approach offers increased statistical power and sensitivity to potentially subtle effects.

The mean overall score on the STAI trait scale was 38.21 (*SD* = 9.50) and the mean overall score collapsed across all time points on the STAI state scale was 34.42 (*SD* = 7.63). The mean overall score on the IUS-12 was 28.72 (*SD* = 9.96). STAI trait and state scores were positively correlated ($r = 0.64$). IUS-12 scores were positively correlated with STAI trait ($r = 0.51$) and state scores ($r = 0.56$).

Inspection of Table 2.2 reveals a number of important effects and interactions. First, IU is positively associated with false alarm rate and also interacts with verbal WMC (see Figure 2.8). The overarching explanation is that low verbal WMC paired with increased symptoms of IU changes the decision threshold employed by participants to respond 'target-present' such that the false alarm rate increases. This effect was more pronounced at low, compared to high, target prevalence and there was also a corresponding effect in the eye movement record in terms of the number of fixations made, with low verbal WMC paired with increased IU symptoms being associated with an increased number of fixations. Second, spatial WMC and IU interact with respect to the extent of predictive first fixations (see Figure 2.8). When spatial WMC and IU are low then there is a reduced likelihood of first fixating targets as TPDs. Third, some effects are only evident in conditions of low or high target prevalence. Shorter scanpaths and lower numbers of fixations were found at low prevalence relative to high and IU was positively associated with the number of fixations at low but not high prevalence. It was also only in conditions of high target prevalence that trait anxiety was positive related to scanpath length.

Table 2.2

Generalised Linear Mixed Models on the Effects of Target prevalence, Working Memory Capacity (WMC), Anxiety and Intolerance of Uncertainty (IU) upon Hit Rate, False Alarm Rate and Colour Steps (limited to 0 or 1) from the Target Colour at First Fixation and Linear Mixed Effects Models for Response Time (RT) and Eye Movement Measures of Trial Total Scanpath Length, Trial Total Number of Fixations and Fixation Duration (standard errors of estimates are shown in parentheses and dashes indicate that a factor was not included in a particular model)

	Hit Rate	False Alarm Rate	RT	Color Step At First Fixation	Trial Scanpath Length	Trial Number Of Fixations	Fixation Duration
Constant	2.53* (0.15)	0.37 (0.23)	7.73* (0.04)	−0.17 (0.12)	630.17* (31.98)	114.01* (4.65)	5.55* (0.03)
Target Prevalence	-	−2.64* (0.14)	-	-	61.60* (1.10)	3.89* (1.19)	-
Verbal WMC	2.66 (1.43)	−2.17 (1.95)	−0.39 (0.34)	−1.24 (1.26)	340.86 (287.67)	60.19 (46.01)	−0.18 (0.28)
Spatial WMC	-	-	-	0.85 (1.00)	-	−54.67 (41.38)	-
IU	−0.01 (0.02)	0.07* (0.02)	0.002 (0.004)	−0.002 (0.01)	−0.10 (3.51)	0.21 (0.46)	−0.002 (0.003)
Trait Anxiety	-	-	-	-	1.31 (3.56)	-	-
Target Prevalence x IU	-	−0.03* (0.01)	-	-	-	-	-
Target Prevalence x Trait Anxiety	-	-	-	-	2.97* (0.97)		-
Verbal WMC x IU		−0.41* (0.17)	-	-	-	−8.60* (4.08)	0.05 (0.03)
Spatial WMC x IU	-	-	-	−0.33* (0.12)	-	-	-
Observations	1,988	2,657	1,829	1,783	1,448	1,448	1,448
Log Likelihood	−533.42	−1,022.08	−1,686.57	−1,191.72	−8,704.56	−5,599.90	1,613.21
Akaike Inf. Crit.	1,074.84	2,058.17	3,383.15	2,395.45	17,425.12	11,215.79	−3,214.41
Bayesian Inf. Crit.	1,097.22	2,099.36	3,410.71	2,428.36	17,467.34	11,225.02	−3,182.74

Note: *p<0.05

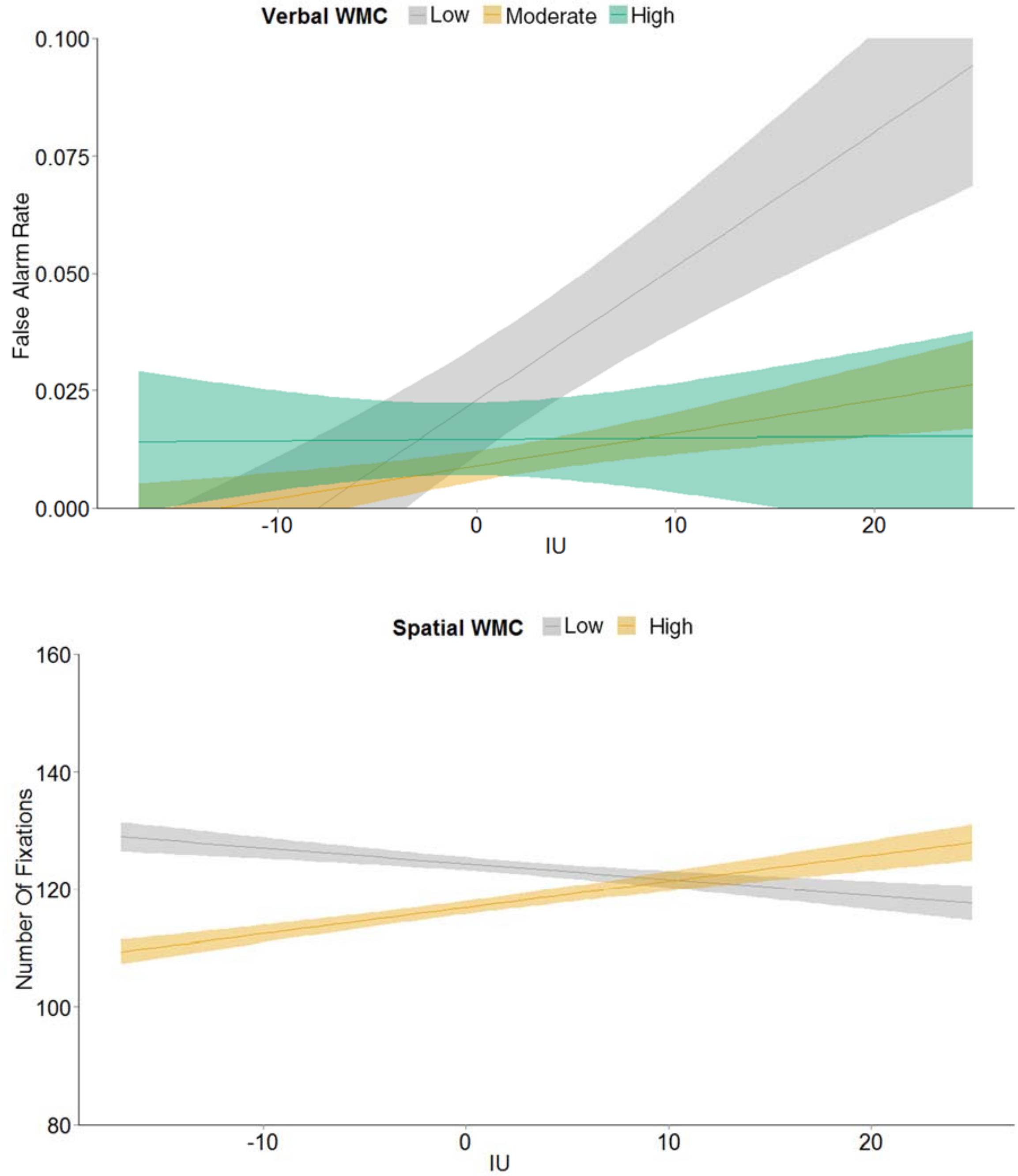

Figure 2.8. False alarm rate and intolerance of uncertainty (IU) at low, moderate and high levels of verbal working memory capacity (WMC; top) and number of fixations and IU at low and high levels of spatial WMC (bottom; shaded regions show continuous 95% CIs). Verbal WMC was split at the 33rd and 66th percentiles to give three categories and spatial

WMC was split at the median to give two categories. This categorization is only for the purposes of visualization and these data were included in all analyses as continuous data.

2.4.3 Discussion

Experiment 3 confirmed the basic findings from the ordered conditions in Experiments 1 and 2. Participants monitored target-predictive distractors and this was the case even when targets occurred very rarely. In addition, low target prevalence led to an overall increase in false alarm rate, i.e., incorrectly classifying distractors as targets, slowed response times (although this effect was only evident when comparing means) and individuals with increased IU symptoms were particularly susceptible to this effect. Low target prevalence also led to an overall shift in search strategy evident by reduced scanpath lengths and the number of fixations made.

In terms of simple behavioural measures, individual differences predicted the false alarm rate, however, they also predicted a range of eye movement measures. Specifically, there was an influence of IU, across false alarm rate and eye movement measures, in interaction with either spatial or verbal WMC. A simple characterization of the pattern of results is that IU is problematic for predictive search when associated with low spatial or verbal working memory. A consequence of increased IU symptoms combined with low verbal working memory capacity is increased false alarms and number of fixations. A consequence of increased IU symptoms combined with low spatial working memory is the reduction in predictive search. The importance of this finding is considered further in the General Discussion. The pervasive influence of IU on behavioural and eye movement measures contrasts with the more limited influence of trait and state anxiety upon eye movements. Trait and state anxiety did not have any main effects upon eye movements.

2.5 General Discussion

Previous literature on visual search has largely been restricted to searching for targets in static displays. This study aimed to extend this to explore target detection in dynamically changing colour displays. The aims were twofold: (1) to examine evidence for predictive monitoring in dynamically changing colour displays for the onset of targets and (2) to identify a set of individual factors that support effective monitoring and target detection.

The results of Experiments 1 - 3 directly addressed the first aim. Target detection was no more accurate or faster when displays changed according to an ordered scale compared to when changes were randomized, but was least accurate and slowest in the shuffled condition of Experiment 2. In all experiments, items that changed according to a psychologically ordered colour scale led to fixations being made to target-similar distractors that were potentially predictive of target onsets (see also Donnelly et al., 2006). These data were consistent with participants using a broad template to help locate possible targets, however, this process was error prone and false alarms were made. Further, while the use of prediction was associated with specific types of error, it never had a negative impact on the overall speed or accuracy of target detection and the results of Experiment 1 suggest that it allowed more forthcoming targets to be identified.

Contrasting the randomized condition of Experiment 1 with the shuffled condition of Experiment 2 revealed a second important result. The presence of arbitrarily defined structure within the colour changes interfered with target detection more than randomized changes. This result has significant implications for how dynamically changing data should be visualized. Given that the pseudo-colouring of images cannot be done on random grounds, colour scales must translate whatever property is being imaged meaningfully to the properties of psychological colour space. Scales that are ordered in a way that does not conform to psychological colour space will likely lead to misses.

The explanation offered for the raised false alarm rate when first fixating distractors as TPDs in the ordered condition is that they are first identified using a broad template. Having been prioritized for monitoring, target detection requires a second match to a more tightly specified template and it is this second match that leads to false alarms. Experiment 3 highlighted a set of individual characteristics that can be used to identify those most likely to make false alarms, specifically the combination of high IU and low verbal WMC. In other words, those most likely to produce monitoring errors when responding to target onsets can be predicted. There is face validity to why low verbal WMC and IU might lead to increased false alarm rates. Holding back 'target' responses when items are similar to targets require maintenance of broad and specific target templates, judgment and patience. Reduced capability to sustain templates, allied to discomfort in maintaining ambiguity lead to a tendency to make affirmative 'target' decisions. The roles that WMC and IU have in determining eye movements in the predictive monitoring task reported here are reminiscent of other recently reported studies indicating that associations between performance in cognitive tasks with symptoms of anxiety is most evident for individuals with low attentional control (Berggren & Derakshan, 2013). Moreover, the present findings are consistent with a search strategy reflecting a hypervigilant broadening of attention in individuals with low IU and low WMC (review by Richards et al, 2014). A practical outcome of this finding is that an assessment of IU and WMC might be particularly beneficial in selecting personnel for scenarios where the cost associated with a false alarm to a colour target onset is critical (for example, when monitoring visual displays for threat in battlefield scenarios).

Experiment 3 found no evidence that target prevalence influenced the manner of predictive monitoring or overall hit rate. However, when considered in terms of the total time for which targets were present, both the high and low prevalence conditions of Experiment 3 involved relatively low target prevalence levels. This suggests that, in dynamic tasks, it is important to consider target prevalence not only in terms of the percentage of target-present trials, but also in terms of the percentage of the total display time for which targets are present. It is possible that in conditions of higher target prevalence, and the increased cue validity of TPDs that this would entail, predictive detection might be associated with a reliable benefit to performance. The use of a liberal criterion to identify targets in low prevalence search suggests that target prevalence may act differently in the present paradigm, compared to how it influences search in more traditional visual search tasks where reducing prevalence is associated with the adoption of increasingly conservative response criteria (Wolfe & Van Wert, 2010). While in need of further study, these data suggest a need to consider how the prevalence effect generalizes beyond simple visual search.

2.6 Conclusions and Implications

The present study examined target detection within dynamically changing visual displays. When displays changed according to a psychologically ordered colour space, target-predictive distractors located one colour step either side of the target colour were prioritized and monitored. While the ability to predict and monitor potential targets was not associated with any improvements in overall task performance compared to randomized displays, displays that changed according to a shuffled colour space interfered greatly with performance. It is concluded that participants use a broad attentional template to prioritize distractors for monitoring when stimulus conditions allow, but at the cost of an inflated risk of making false alarms. The results of Experiment 3 further suggest that individuals who are high in intolerance of uncertainty and low in verbal working memory capacity are particularly susceptible to making false alarms.

The results of Experiments 1 – 3 have clear implications for how we use colour to represent dynamically changing data values. Principally, when choosing how to use colour to represent dynamically changing data, a psychologically ordered colour scale will allow those monitoring to predict likely target onsets. Incremental changes on such a scale will also maintain the continuity of colour change, avoiding abrupt, highly salient, colour changes that can interfere with target detection. That said, there are some for whom the use of an ordered colour comes with a risk, specifically, individuals with high IU and low verbal WMC. The increased false alarm rates for these individuals suggest they may not be suited to such monitoring tasks, especially if there are significant risks or costs associated with pre-emptive target responses, such as in the military domain. These attributes are quick and easy to assess and could be used to test individual aptitude for monitoring dynamic visual displays. In summary, the current study has pointed to issues of concern in how best to represent dynamically changing colour information to allow target detection and the predictive monitoring for target onsets, and who might perform these types of task well.

Chapter 3

Examining the Impact of Working Memory Training and Transcranial Direct Current Stimulation on Monitoring for Colour Targets

3.a Abstract

A variety of real-world visual tasks involve monitoring electronic displays of items that change dynamically over time. Chapter 2 showed that when monitoring dynamic displays for colour targets: (1) contingencies between targets and distractors facilitated predictive target detection; and (2) elevated intolerance of uncertainty (IU) and lower verbal working memory capacity (WMC) were associated with a higher false alarm rate. The present study employed the same dynamic colour search task used in our previous research. In addition to attempting to replicate previous findings, this study examined whether search performance was improved following two placebo-controlled interventions: adaptive dual *n*-back working memory (WM) training and transcranial direct current stimulation (tDCS) of the dorsolateral prefrontal cortex (DLPFC). Participants searched for colour targets in arrays of dynamically changing coloured squares before and after receiving either WM training or tDCS. The results showed that targets were detected predictively, following their fixation as target-similar distractors, and that this improved response times. In addition, elevated IU and higher verbal WMC were identified as significant predictors of a higher hit rate. An account is provided that links the effects of IU and WMC capacity with results from previous work in terms of variation in response criterion and perceptual sensitivity. There was no evidence that active WM training or tDCS significantly improved performance on the search task, WMC or attentional control relative to controls. The null results of the two interventions add to a mixed literature on the efficacy of WM training and tDCS, however, the basic findings of this study extend our understanding of dynamic

search tasks and have implications for the selection of personnel in a variety of real-world scenarios.

3.1 Introduction

Increased spatial and verbal working memory capacity (WMC) have been positively associated with performance in challenging visual search and target detection tasks (Anderson, Mannan, Rees, Sumner, & Kennard, 2008; Schwark, Sandry, & Dolgov, 2013; Woodman & Luck, 2004). In individuals who report elevated anxious affect, WMC can be consumed when attentional resources are prioritized to task-irrelevant internal (e.g., worrisome thoughts) and external (e.g., potential negative feedback from others) information (see reviews by Derakshan & Eysenck, 2009; Eysenck & Derakshan, 2011; Eysenck, Derakshan, Santos, & Calvo, 2007; Richards, Hadwin, Benson, Wenger, & Donnelly, 2011). In individuals with low WMC, this can leave little capacity remaining for allocation to other tasks. In Chapter 2, it was found that when monitoring for targets in a dynamic colour search task, target detection was influenced by individual differences in verbal WMC and intolerance of uncertainty (IU), a component of trait anxiety that relates specifically to uncertain future events (Birrell et al., 2011). The novel search task used in these experiments involved displays of fixed-location coloured squares, that changed dynamically over extended trial durations. This task allowed for the examination of target monitoring and prediction processes that are relevant to a wide range of real-world scenarios. The results were consistent with the use of a broad target template to prioritize and monitor potential targets.

Specifically, Chapter 2 found evidence that symptoms of IU were positively associated with false alarm rate in a dynamic search task. This relationship was moderated by verbal WMC, such that increased WMC reduced the effect of IU on the false alarm rate. This finding is consistent with the proposed compensatory role of WM, as outlined by theoretical frameworks of anxiety and cognition (Derakshan & Eysenck, 2009; Eysenck & Derakshan, 2011; Eysenck et al., 2007), which suggest that the impact of anxiety on attentional control may be most evident in individuals who have limited WM resources. This finding was also consistent with eye movement evidence that showed that individuals with high IU and low verbal WMC made a greater number of fixations, suggesting reduced processing efficiency. These findings fit with a broader pattern of results which highlight the importance of attentional control and WM in understanding the cognitive effects of anxiety, and suggest a protective role for these factors that moderates the impact of elevated anxiety on cognitive processing (Booth, Mackintosh, & Sharma, 2017; Hadwin, Visu-Petra, Muris, Derakshan, & MacLeod, 2016; Matthew Owens et al., 2014).

In addition to examining individual differences in anxiety and WMC, our previous experiments investigated the effects of target prevalence within a dynamic search task. The effect of low target prevalence is well-established within the visual search literature, specifically, when targets are rare there is a behavioural cost to detection speed and accuracy (Wolfe et al., 2007, 2005). Evidence suggests that the primary source of this effect is via a criterion shift that influences the perceptual identification of targets, combined with a tendency to quit searching more rapidly when prevalence is low (Godwin, Menneer, et al., 2014; Wolfe & Van Wert, 2010). In other words, when targets are rare, individuals require more perceptual evidence to make a 'target-present' response, resulting in misses and slowed responses. Conversely, when targets are common, individuals require less perceptual evidence to make a target-present response, resulting in speeded responses and increased false alarms. Target prevalence has typically been considered in terms of the percentage of target present trials, which is a sensible conceptualization for experiments that involve series of static trials with relatively short durations. However, in the case of dynamic trials with longer durations, where it is not possible for participants to 'quit' search and respond ‘target-absent’, simply considering whether a target was present in the trial is less helpful than considering the amount of time for which targets were present (as a proportion of the total combined trial durations). Target prevalence may, therefore, be very low even when targets are present in a high proportion of trials and this was an important consideration in setting target parameters for the present study.

In addition to attempting to replicate and extend previous findings to higher levels of target prevalence, this study explored two interventions with a view to improving task performance via benefits to WMC and attentional control (and specifically the moderating effect of WMC on IU). The first of these interventions was a program of WM training. WM training typically involves a computerized adaptive complex span or *n*-back type task that loads heavily upon WM (see reviews by Au et al., 2014; Au et al., 2016; Melby-Lervåg & Hulme, 2015). Participants complete these tasks regularly and over multiple days, and the difficulty of training is adapted to individual performance that reflects shifts in the number of items or steps to be remembered. Training is typically assessed by performance improvements within the training sessions, as well as benefits to untrained tasks.

The “near transfer” of benefits to untrained tasks that are similar to the training task is commonly reported (e.g., Brehmer, Westerberg, & Bäckman, 2012; Klingberg, Forssberg, & Westerberg, 2002; Westerberg & Klingberg, 2007), but the evidence supporting more “distant transfer” to tasks that capture the broader generalization of training effects is more mixed. While many studies have failed to obtain significant training benefits of this type (review by Shipstead, Hicks, & Engle, 2012), some key studies have shown improved fluid intelligence (Jaeggi et al., 2008, 2012) and attentional control (Max Owens et al., 2013) following WM training.

The second intervention in the present study was based around transcranial direct current stimulation (tDCS), a non-invasive brain stimulation technique which modulates cortical excitability via the delivery of a very weak electrical current (typically between 1 and 2 mA) through electrodes placed on the scalp (Nitsche et al., 2008). Early research showed that neuronal depolarization at the anodal stimulation site resulted in a localized increased likelihood of neuronal firing and a converse effect at the cathodal stimulation site (Nitsche & Paulus, 2000) and, while much of this early research involved stimulation of the motor cortex (e.g., Nitsche & Paulus, 2000, 2001; Rosenkranz, Nitsche, Tergau, & Paulus, 2000), this technique has since been applied to other brain regions, including prefrontal areas. The dorsolateral prefrontal cortex (DLPFC) has important roles in high level cognition, including WM and the executive control of attention (Lara & Wallis, 2015; Rossi, Pessoa, Desimone, & Ungerleider, 2009), and has often been targeted in tDCS studies with a view to improving these functions (Tremblay et al., 2014). Stimulation of the DLPFC has been associated with a wide range of outcomes, including improvements in associative learning (Kincses, Antal, Nitsche, Bártfai, & Paulus, 2004), recognition memory (Pergolizzi & Chua, 2017; Smirni, Turriziani, Mangano, Cipolotti, & Oliveri, 2015; Zwissler et al., 2014), verbal fluency (Iyer et al., 2005), anxiety-related attentional bias (Clarke, Browning, Hammond, Notebaert, & MacLeod, 2014), risk taking behaviour (Fecteau, Knoch, et al., 2007), processing emotional stimuli (Boggio et al., 2007), WM (Berryhill & Jones, 2012; Fregni et al., 2005; Keeser et al., 2011; Mulquiney, Hoy, Daskalakis, & Fitzgerald, 2011; Teo, Hoy, Daskalakis, & Fitzgerald, 2011) and the executive control attentional network (Miler et al., 2017).

The present study builds on previous work in three ways. Firstly, by extending the conditions examined in Chapter 2 to a higher level of target prevalence. It is predicted that the impact of the higher level of target prevalence in the present task will be to improve behavioural performance (hit rate, response time, false alarm rate) and increase predictive target detection relative to previous findings at lower prevalence. Secondly, this study seeks to confirm the interaction between IU and verbal WMC with respect to target detection in these new experimental conditions. It is expected that, once again, IU will be found to predict false alarm rate and the number of fixations and that these effects will be found primarily in individuals with low verbal WMC. In addition to the number of fixations, eye movement measures of fixation duration and scanpath length are also examined for related effects that might reflect a more active monitoring strategy, for example, shorter fixation durations and longer scanpaths. Thirdly, this study explores if attempts to increase WMC by WM training or tDCS might improve target detection by moderating the impact of IU on target detection. It is predicted that active WM training and tDCS will provide a particular benefit to target detection for those with greater symptoms of IU relative to controls.

3.2 General Method

3.2.1 Design

In the case of both the WM training and tDCS interventions, the primary independent variables were the type of intervention, active or control (placebo/sham), which was manipulated between participants, and the time, pre- or post-intervention, which was manipulated within participants. The primary dependent variables for the search task included behavioural measures of response time (RT), hit rate and false alarm rate, and eye movement measures of the proportion of first fixations on targets and target-predictive distractors at 1 and 2 colour steps from the target colour, the number of fixations, fixation duration and scanpath length. In order to explore the near and distant effects of both interventions on WMC and attentional control, additional measures were included from a visual digit span, a visuo-spatial change detection task, an antisaccade task and the

Attention Network Test (ANT). Individual differences in IU were also recorded to explore its relationship with search performance.

3.2.2 Apparatus and Materials

For all computerized tasks completed in the laboratory, stimuli were displayed on a 21" CRT monitor operating at a resolution of 1,024 x 768 pixels and a refresh rate of 120 Hz. The visual search task and antisaccade tasks were controlled using a computer connected to an SR Research EyeLink 1000 eye-tracker operating at a sampling rate of 1,000 Hz. The task was administered using the same procedure as in Chapter 2. A nine-point calibration procedure was used and calibration was accepted only when none of the points had an error of more than 0.5° of visual angle. For the antisaccade task, a three-point calibration procedure was used and calibration was accepted only when none of the points had an error of more than 1.0° of visual angle. For both of these tasks, participants were seated 70 cm from the display, the display was viewed binocularly, although only the right eye was tracked, and a chin rest was used to keep participants' heads stable during the experiment. These tasks were programmed using Experiment Builder from SR Research with additional code written in Python. Participants responded using a Viglen USB optical mouse.

3.2.3 Visual Search Task

Stimulus displays were generated on a trial-by-trial basis and all angles in this section are visual angles calculated from the centre of the display (values vary marginally for more eccentric locations). Individual coloured squares (items) were 0.57° x 0.57°, and displayed in irregular 12 x 9 arrays. Items never abutted, but were randomly 'jittered' within the constraints of an invisible grid, such that each stimulus appeared within an area of 2.15° by 2.15°, which was used to code fixations. The maximum size of the whole array of colour stimuli was 24.78° x 18.36° and 108 items were always present.

Stimuli were coloured using a 16-item colour scale (see Menneer et al., 2007). For each participant, one colour was the target (T) and 15 colours were distractors (D). Of the 108 coloured squares, 96 squares were always at least 3 steps away from being a target and these were considered background distractors. There were 12 squares that could display colours within 2 colour steps of the target. The locations of these 12 squares were varied across trials and, unknown to participants, these were never located at the edge of the array or immediately adjacent another of these 12 squares. The target colour was varied and counterbalanced between participants, such that each colour was the target for at least one participant (Figure 3.1 shows the full colour scale).

The search task was always administered in a single 72-trial block with a self-paced break at the halfway point and, within this, 36 trials had up to five targets present and 36 trials were target absent. The total number of targets presented over the course of each target present trial was dependent upon participant performance and the restriction that no more than one target could be present at any one time. Failing to detect an earlier target could delay or exclude the onset of later targets. Participants were shown a static sample display (see Figure 3.2) and were given a practice block of three trials was given before beginning the task. Trials began with a 1 s reminder of their target, followed by a 1 s fixation point. Each trial lasted 40 s (see Figure 3.3) and audio feedback was given for every response (to indicate whether it was correctly made to a target or not). Participants were told to search for a target square defined by a particular colour, which was shown before every trial, and to respond as quickly as possible by clicking the mouse cursor on the target. Participants were told that trials might contain more than one target but only one target would be visible at any given time.

Trials began with all items as background distractors. Stimulus arrays were updated with a variable refresh rate and this resulted in displays that refreshed at a mean rate of once every 105 ms (*SD* = 96) and the mean rate of colour change for each item was a change every 339 ms (*SD* = 352). Background distractors in both conditions could change between the 11 colours that were at least three steps from the target colour. When changing colour, items could change to be closer to, or further from, the target colour. For background distractors, these two possibilities were equally likely, other than when three steps from the target colour. At certain time points during trials, the 12 squares that could display colours within two steps of the target were allowed to change across the full range of 16 colours (or 15 colours if they were not to become a target). As there were up to five targets per trial, at least seven of these 12 stimuli reached a colour one step from the target, but never achieved a target state. The effect of these conditions was to allow stimuli to systematically approach the target colour, allowing the colour of distractors to be used as a predictive cue to the onset of targets.

Each of these 12 items was given a number of key properties, all independently and pseudo-randomly generated within Python: (1) a time at which they were allowed to move within two colours of the target; (2) a time after which they will become a target or a distractor colour one step from the target; and (3) a duration for which they remain present as target or a distractor one step from the target before reverting to background distractor (if no response was made). These values corresponded to the first T onset after an average of 9,362 ms (*SD* = 3,929). On average and where applicable, the second T onset occurred after 14,860 ms (*SD* = 4,490), the third T onset occurred after 20,159 ms (*SD* = 5,441), the fourth T onset occurred after 24,453ms (*SD* = 5,266) and the fifth T onset occurred after 29,076 ms (*SD* = 5,193). This also resulted in an average duration of targets, if no response was made, of 1,347 ms (*SD* = 739). If there was no response was made to a target, the item timed-out and was reset to a background distractor. Responding target-present (irrespective of whether it was a hit or a false alarm) also caused it to reset to a background distractor.

While up to five targets might be presented over the course of a trial, only one target could be present at any given time. The parameters that controlled stimulus behaviour were selected based on the work presented in Chapter 2.

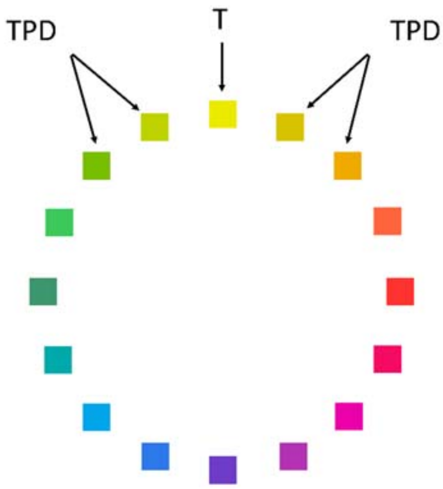

Figure 3.1. Full colour scale showing example target predictive distractors when the target was the indicated colour.

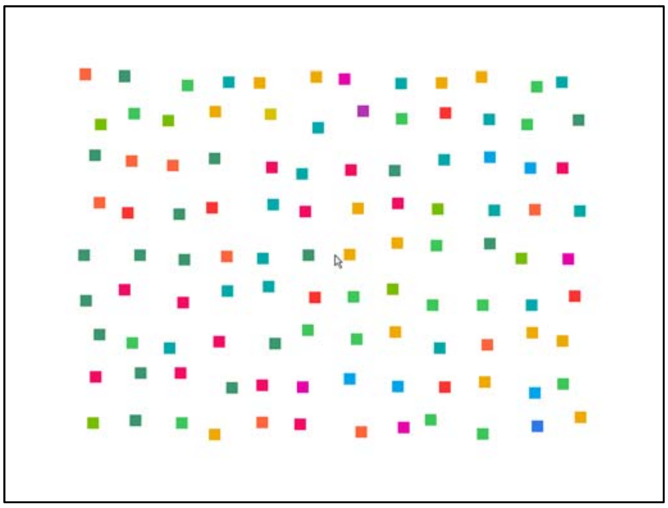

Figure 3.2. Sample stimulus display.

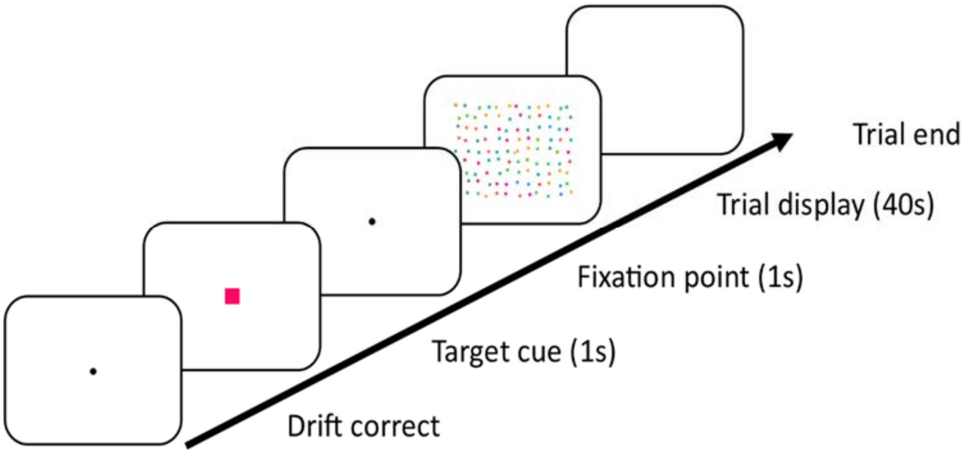

Figure 3.3. Trial sequence.

3.2.4 Working Memory Capacity and Attentional Control Tasks

3.2.4.1 Visual digit span. The digit span task used was developed by Borchert (2016) and follows the procedure detailed in Woods et al. (2011). In each trial of this task a sequence of digits (0 to 9 inclusive) was presented one-at-a-time in the centre of the display and, when a sequence had finished, participants were required to enter the digits in a text box using the keyboard. The task was divided into two blocks. In the first block participants were required to enter digits in the same order in which they were presented and in the second block digits needed to be entered in reverse order to presentation. If the sequence of digits was entered correctly, then the sequence length was increased by one digit. If the sequence of digits was entered incorrectly twice consecutively, the task continued, but the sequence length was reduced by one digit (not below the starting level). In the forward block, the sequence length began at three digits and in the backward block at two digits. Participants were given a single practice trial at the initial sequence length before beginning each block and each block contained at least 14 trials (contingent upon performance). Performance was reflected in the maximum sequence length recalled correctly before making two consecutive errors.

3.2.4.2 Change detection task. This task follows the procedure used by Owens et al. (2012; 2013). Trials involved two stimulus arrays, a memory array and a test array, which consisted of red and blue rectangles. Participants were required to remember the orientation of target items (red stimuli), from either the left or right side of the memory array and respond, with one of two button presses, to indicate whether or not the orientation of one of these stimuli had changed in the test array. 50% of trials involved a change and stimuli were viewed at a distance of 70cm. Each array consisted of two regions (5.99° x 9.04°), each containing two or four rectangles. Regions were centreed 4.22° left and right of a central fixation cross. Each rectangle was randomly assigned one of four orientations (vertical, horizontal, left 45°, right 45°) and could be either red (target) or blue (distractor). Each trial began with a central fixation cross and a white arrow cue, pointing left or right, visible for 700 ms. Participants were instructed to maintain fixation on the cross during each trial, but to attend to the side indicated by the arrow. After presentation of the cross and arrow, the left and right regions showed 2 red rectangles, 4 red rectangles or 2 red rectangles and 2 blue rectangles for 100 ms (memory array). Only the cross was then displayed for 900 ms (retention period) and then the rectangles were redisplayed for 2,000 ms (test array). The inter-trial interval was randomly set at either 1,500 ms or 2,000 ms. Array size, arrow direction, change and no-change trials were randomized and had equal prevalence across the experiment. Participants completed a practice session of 24 trials (8 per condition) before the main task. The task was divided into 4 blocks of 48 trials (64 trials per condition), totaling 192 trials across the experiment. A short break was given after each block. Performance was reflected in the proportion of correct responses (hit rate).

3.2.4.3 Attention Network Test. The ANT combines a flanker task and a cued reaction time task to provide measures of attentional orienting, altering and executive control (Fan et al., 2002, 2005). In the present case, this task consisted of 8 randomized practice trials followed by 64 randomized experimental trials. On each trial a central fixation cross was presented for 400–1,600 ms, followed by a cue for 100 ms (except on no-cue trials). Subsequently, 400 ms after cue offset (or 500 ms in no-cue trials), target and flanker arrows were displayed until the participant made a manual button press response. On double cue trials the cue was displayed both above and below the fixation cross and alerted participants to the onset of the target (but not spatial location). On centre cue trials the cue was displayed in the location of the fixation cross and alerted participants to the onset of the target. In contrast, on spatial cue trials the cue was displayed above or below the fixation cross and signaled both the onset and spatial location of the target (always displayed in the location of the cue), thus orienting attention towards the location of the pending target. Participants were instructed to classify as quickly and accurately as possible whether the central (target) arrow pointed left or right. The target arrow was flanked by two pairs of distracter arrows. Flanker arrows either pointed in the same direction (congruent condition) or opposite direction (incongruent condition) as the target arrow. Flanker congruence, target direction and target location were counterbalanced across spatial, double, centre and no-cue trials and RTs were collected via keyboard button press. The task sequence and all cue and target types are shown in Figure 3.4.

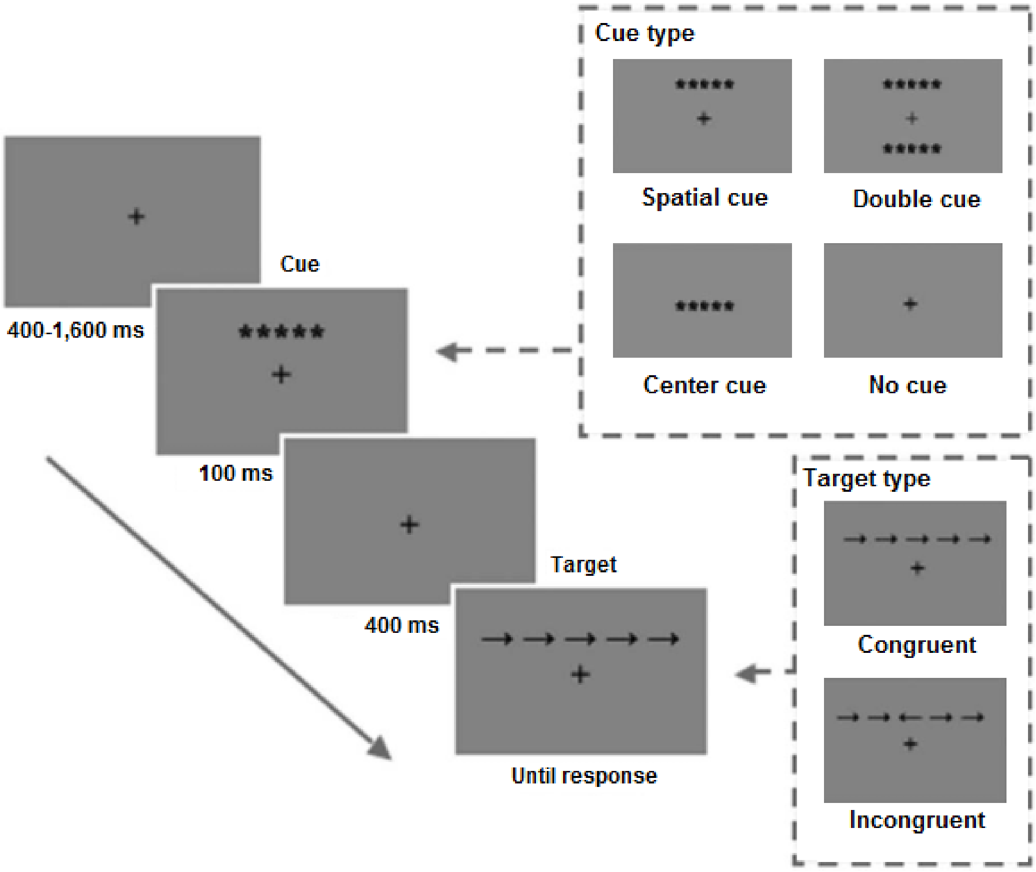

Figure 3.4. Attention Network Test task sequence with all cue and target types (figure adapted from Garner et al. [2012]).

3.2.4.4 Antisaccade task. The antisaccade task was adapted from that used by Hepsomali, Hadwin, Liversedge and Garner (2017). It consisted of a short practice block of 10 trials and then two blocks of 100 trials. Each trial began with the presentation of central letter cue, ‘O’ or ‘X’, to indicate whether a pro- or antisaccade should be made respectively. This was then replaced with a fixation cross which remained visible for either 1,000 ms or 3,000 ms, before a grey ellipse (4.59° x 3.66°) appeared on either the extreme left or right hand side of the display. The side of the display where the ellipse was presented, the delay and the type of saccade required were counterbalanced and the order of trials was randomized. On prosaccade trials participants were instructed to look at the ellipse and on antisaccade trials participants were instructed to look at the opposite side of the screen. The ellipses were displayed for 1,500 ms. Performance was measured in terms of the accuracy (whether the correct type of saccade was made) and latency of the first saccade made after stimulus onset.

3.2.5 Anxiety and Mood Measures

3.2.5.1 Intolerance of uncertainty. The Intolerance of Uncertainty Short Form (IUS-12; Carleton et al., 2007) is a 12-item self-report measure that assesses reactions to uncertainty, ambiguous situations and future events. It consists of two factors, the first, prospective IU, relates to worry regarding future events and is assessed by 7 items, for example, “I can’t stand being taken by surprise.” The second, inhibitory IU, relates to the extent to which uncertainty might inhibit action or experience and is assessed by 5 items assessing, for example, “when it’s time to act, uncertainty paralyses me”. Each response is made on a five-point scale which ranges from 1 “not at all characteristic of me” to 5 “entirely characteristic of me” and this results in a total score between 12 and 60. In the current study the reliability of the scale was good ($\alpha >= .81$).

3.2.5.2 Visual analogue scales. Visual analogue scales (VAS) were used to measure participants’ mood at three time points during both visits in both interventions (see Wewers & Lowe, 1990): (1) before completing the visual search task; (2) after completing the visual search task; and (3) at the end of the session. The VAS asked participants to rate the extent to which they felt anxious, alert, happy, able to concentrate, relaxed, worried and tired. For the second and third VAS of each session, a further item was included that asked participants how hard they tried. Participants responded to each VAS item by making a mark on a dotted line, allowing for continuous responses, however, for guidance, each line was labelled (from left to right) ‘not at all’, ‘a little’, ‘moderately’, ‘quite a bit’ and ‘extremely’. Each item was scored between 0 and 160 using the distance of the response along the line.

3.2.6 Procedure

Participants were tested for normal visual acuity and colour vision using the Freiburg Visual Acuity Test (Bach, 1996) and the City University Colour Vision Test (3^{rd} edition; 1998). To maximize comparability between the two interventions, the same safety screening was applied to all participants before they were allowed to enter the study. This involved a brief medical history and a neuropsychiatric interview based on the M.I.N.I. International Neuropsychiatric Interview (Sheehan et al., 2006).

Participants made two visits to the laboratory. On each visit, both pre- and post-intervention for both memory training and tDCS, the same procedure was followed with the exceptions noted in the sections below. Participants completed the IUS-12 before completing the search task on the first visit. After the search task, participants completed the antisaccade task, the ANT, the digit span task and the change detection task in that order. Self-timed breaks were given to participants between blocks in the antisaccade task and before starting each new task.

3.3 Working Memory Training Method

3.3.1 Participants

20 students (14 female) from the University of Southampton participated in the working memory training intervention for partial fulfilment of a course requirement or for compensation of £78. Their mean age was 20.95 years (SD = 2.37; Range 19 to 26 years). All participants had normal visual acuity (at least 1.0 decimal VA at 70cm), tested using the Freiburg Visual Acuity Test (Bach, 1996) and normal colour vision, tested using the City University Colour Vision Test 3rd Edition (Fletcher, 1998).

3.3.2 Training Task

A dual *n*-back task was used (Jaeggi et al., 2008; Max Owens et al., 2013). In the task, participants were shown a 3 x 3 grid, with a fixation cross in the centre. In each trial, a green square appeared in one of the eight outermost locations in this grid and, paired with each presentation of a square (within 500 ms) one of eight consonants (c, h, k, l, q, r, s, and t) was spoken (see Figure 3.4). There was a delay of 2,500 ms between trials. Participants were told to remember both the location of the green square within the grid and the letter that they had heard and to respond if either of these stimuli matched a letter or location presented *n* trials back in the sequence. Participants responded using a keyboard and pressed the 'A' key for visual matches and the 'L' key for auditory matches (sometimes the correct response was to press both of these at the same time). No response was required if there was no match and participants were told to respond as quickly and accurately as possible. Participants completed this dual *n*-back task online in their own time using a computer of their choosing via a bespoke website that allowed the experimenter to monitor training progress.

In the adaptive training condition, participants in the training group completed 20 blocks of 20 + *n* trials, where *n* was determined by the level of *n*-back (e.g., 2-back, 20 + 2 = 22 trials). Within the adaptive condition, the *n*-back level (which determined task difficulty) was varied based on the percentage accuracy across visual and auditory responses after each block. Each training session began with a block at the 1-back level and after this block, and for every subsequent block in that session, the level of *n* was: increased by one if accuracy was at or above 95% for both modalities; decreased by one if accuracy was below 75% in either modality; and remained unchanged if accuracy was between 75% and 95%. The 4-back level was set as the highest *n*-back level in the study. Participants were reminded of the *n*-back level before each block and this reminder remained visible throughout. In the non-adaptive control condition, the *n*-back level was fixed at 1-back. Participants completed 20 blocks of 20 trials per session. This was to ensure that the control group remained active and performed a similar task to the adaptive training group, but with minimal reliance upon working memory processes. To ensure an equal number of participants in each training condition while maintaining randomisation, group assignment was conducted using a randomly shuffled list. Participants were blind to their group assignment.

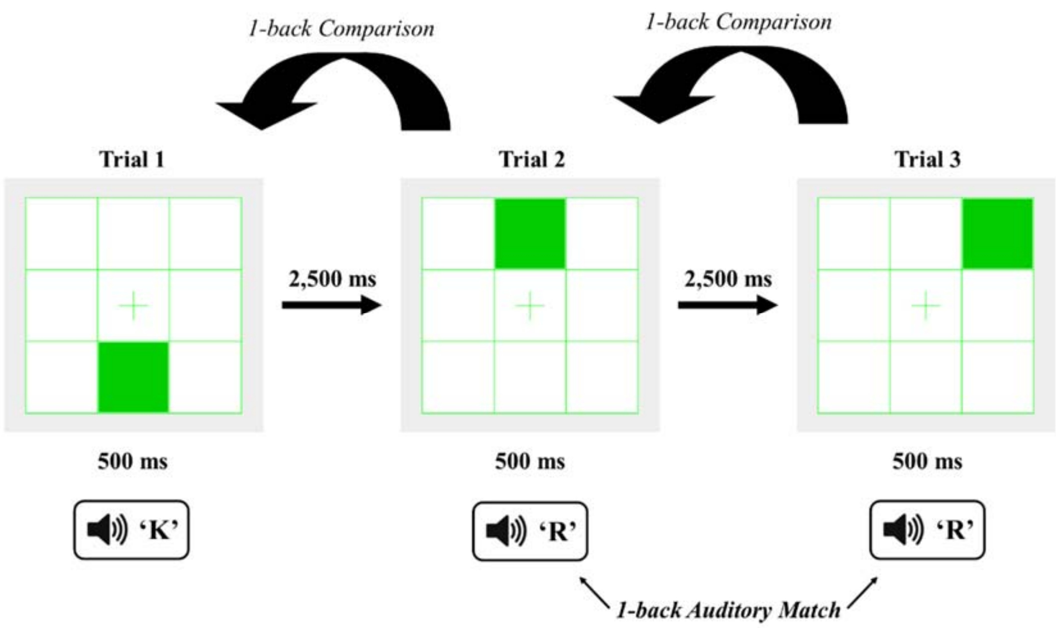

Figure 3.5. A sequence of three trials in the training task at the 1-back level. The correct response would be to press 'L' on the third trial for the auditory match with the second trial.

3.3.3 Training Procedure

Immediately prior to leaving the laboratory at the end of the first visit, all participants completed a practice block of 20 trials on the task at the 1-back level. Later that day, and in their own time, participants completed the first full session of training. In total, all participants completed 15 training sessions, each consisting of 400 trials divided equally across 20 blocks and lasting approximately 30 minutes (participants in the adaptive training condition completed some additional trials dependent upon n-back level). Each block lasted approximately one minute, with a break of 15 seconds was given between blocks, and training sessions could not be paused once started. Targets were varied randomly such that each block had an equal number of visual and audio matches (4 per block) and two trials with a double (auditory and visual) match. Target positions within blocks were also varied randomly such that the value of n was the same for visual and auditory stimuli.

Participants completed the training over a period of 15 to 17 days, such that no more than one training session was completed per day but participants could take up to two break days. Participants' second visit to the laboratory for their post-training assessment was always on the same day as or the day following the final training session. Training performance was monitored by the experimenter and participants were shown a summary of their auditory and visual scores over the session at the end of each block. Figure 3.6 shows the full overall procedure of both interventions.

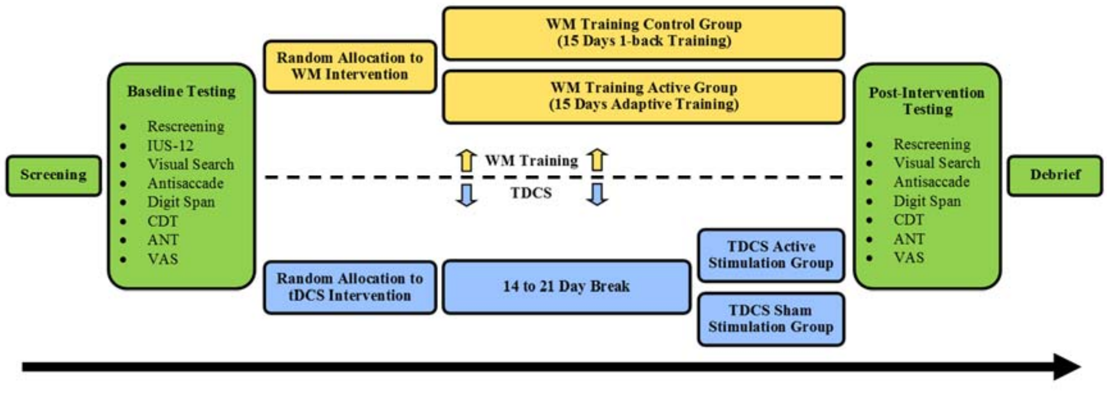

Figure 3.6. Full study procedure, including the Intolerance of Uncertainty Short Form (IUS-12), the dynamic visual search task, the antisaccade task, the digit span, the change detection task (CDT), the Attention Network Test (ANT), and the Visual Analogue Scales

(VAS) across the working memory (WM) training and transcrianial direct current stimulation (tDCS) interventions.

3.4 Transcranial Direct Current Stimulation Method

3.4.1 Participants

26 students (18 female) from the University of Southampton participated in the tDCS intervention for partial fulfilment of a course requirement or for compensation of £39. Their mean age was 21.27 years (*SD* = 2.55; Range 18 to 27 years). All participants had normal visual acuity (at least 1.0 decimal VA at 70 cm), tested using the Freiburg Visual Acuity Test (Bach, 1996) and normal colour vision, tested using the City University Colour Vision Test 3rd Edition (Fletcher, 1998).

3.4.3 Stimulation Parameters

Stimulation was administered bilaterally, with the anode over the left DLPFC and the cathode over the right DLFPC (F3 and F4 respectively according to the 10-20 EEG system). In the active condition, participants received stimulation with a current of 2 mA for 20 minutes and in the control condition participants received sham stimulation (current of 2 mA was applied initially but ramped down to 0 mA after 30 seconds). As with the previous intervention, to ensure an equal number of participants in each training condition while maintaining randomisation, group assignment was conducted using a randomly shuffled list for each intervention. Both participants and researchers were blind to which of the stimulation devices was programmed to administer active and sham stimulation

3.4.3 Stimulation Procedure

Participants received stimulation on their second visit to the laboratory after completing a short re-screening for safety purposes. To maximize comparability with the memory training intervention, the second visit was always at least 14 days, and no more than 21 days, after the first visit. Immediately following stimulation, participants completed the visual search task and the remaining computerised tasks in the standard order. Figure 3.6 shows the full overall procedure of both interventions.

3.5 Results at Baseline

Before examining the efficacy of the two interventions in this study, the baseline (pre-intervention) results were analysed with view to replicating previously established task performance and linking individual differences in WMC and IU with behavioural performance and eye movements. At the same time, the effect of increased target prevalence, relative to Chapter 2, will be assessed via comparisons with behavioural and first fixation measures from the previous dataset. As all baseline data were collected according to the same procedure, data from participants in both interventions (46 total participants) were analysed together.

3.5.1 Transformations and Exclusions

Across all analyses (including post-intervention), RT exclusion criteria were set *a priori* at above 10,000 ms and below 200 ms from target onset, but no responses were outside of these limits. RTs were log transformed before being analysed and untransformed means are reported. In the eye movement data, fixations were excluded from duration analysis if they were longer than 1,200 ms, shorter than 80 ms in duration, or if they corresponded with a manual response (6.31% of all fixations). Proportional data were arcsine square root transformed before being analysed, and untransformed means are reported. Hit rate was defined as the proportion of targets across all trials that were responded to correctly. False alarm rate was defined as the proportion of all responses that were made to non-target stimuli[2].

3.5.2 Behavioural Responses

Table 3.1 shows the hit rate, response time (RT) and false alarm rate at baseline, as well as comparisons with previous results from Experiment 3 in Chapter 2. This previous study employed two prevalence levels that were both lower than the present study (blocks where either 5.6% or 66% of trials contained at least two targets), therefore, for the purposes of this analysis, the prior data were averaged across prevalence levels. The results show the higher target prevalence level in the present task increased hit rate and reduced RTs and FA rate relative to the previous study.

Table 3.1

Mean Basic Behavioural Results from the Present Study at Baseline and Experiment 3 in Chapter 2 with Unequal Variances t-tests

	Chapter 2 Experiment 3	Present Study Baseline	
Hit Rate	0.88 (0.09)	0.94 (0.04)	$t(40.47) = 3.65, p < .001$
Response Time (ms)	2,685 (564)	1,860 (351)	$t(49.55) = 7.43, p < .001$
False Alarm Rate	0.22 (0.21)	0.08 (0.08)	$t(38.79) = 3.72, p < .001$

Note. Standard deviations shown with means in parentheses

[2] Signal detection theory (SDT) measures of sensitivity or response criterion were not calculated due to the non-standard calculation of false alarm rate and, given the dynamically changing nature of the displays, there is no clear determination of what should constitute a correct rejection.

3.5.3 Target Prediction

In line with previous work, distractors that were forthcoming targets are referred to as target-predictive distractors (TPDs). To examine target prediction, first fixations to targets and TPDs were analysed to provide a measure of the state of items when they initially attracted attention. These data were analysed using a one-way (colour step: 0, 1, 2 steps from the target colour) repeated-measures ANOVA. Mauchly's Test of Sphericity indicated that the assumption of sphericity was violated, W=0.51, $p < .001$, so Greenhouse-Geisser corrected results are reported. There was a significant effect of colour step on the proportion of first fixations to targets and forthcoming targets, $F(1.35, 60.62) = 207.60$, $p < .001$, $\eta^2_G = 0.82$. Pairwise comparisons revealed a significant difference between the proportion of first fixations made at 0 steps and 1 step, $t(45) = 4.84$, $p < .001$, 0 steps and 2 steps, $t(45) = 13.51$, $p < .001$, and 1 step and 2 steps, $t(45) = 32.40$, $p < .001$ (see Figure 3.7). Analysis of fixations and re-fixations to targets and TPDs showed means of 4.07 (*SD* = 0.55), 4.20 (*SD* = 0.66) and 2.93 (*SD* = 0.56) total fixations to targets, TPDs at +/- 1 step and TPDs at +/- 2 steps respectively. Background distractors were fixated on average 0.35 times (*SD* = 0.08).

To examine the effects of target prevalence, the proportion of first fixations to forthcoming targets at 0, 1 and 2 colour steps from the target colour were compared to averaged results from Experiment 3 in Chapter 2. Three unequal variances *t*-tests were carried out for the data at T, T +/- 1 and T +/- 2 steps (see Figure 3.7). In the previous study: (1) a significantly greater proportion of targets were first fixated as targets post-onset (*M* = 0.48, *SD* = 0.22), compared to the present study (*M* = 0.37, *SD* = 0.15), $t(54.82) = 3.06$, $p = .003$; (2) a significantly lower proportion were first fixated at T +/- 1 step (*M* = 0.43, *SD* = 0.19), compared to the present study (*M* = 0.53, *SD* = 0.13), $t(50.12) = 3.35$, $p = .002$; and (3) there was no difference in the proportion first fixated at T +/- 2 steps (*M* =

0.07, *SD* = 0.07), when compared to the present study (*M* = 0.07, *SD* = 0.05), $t(57.46) = 0.74$, $p = 0.46$. In the present study, with a higher overall level of target prevalence, a greater proportion of targets were detected predictively, following first fixation one colour step prior to onset.

Next, the effects of predictive monitoring on hit rate, RTs and false alarm rate were analysed. Hit rate was lower when first fixating a TPD one step from becoming a target (*M* = 0.93, *SD* = 0.05), than when first fixating the target itself (*M* = 0.96, *SD* = 0.04), $t(45) = 5.06$, $p < .001$. The false alarm rate was not significantly different when fixating a TPD one step from becoming a target (*M* = 0.12 *SD* = 0.12) from when first fixating a TPD two steps from becoming a target (*M* = 0.13, *SD* = 0.16), $t(45) = 0.71$, $p = .481$. RT was significantly lower when first fixating a TPD one step from becoming a target (*M* = 1,797 ms, *SD* = 363) than when first fixating the target itself (*M* = 1,984 ms, *SD* = 383), $t(45) = 4.51$, $p < .001$.

To summarize these basic behavioural and first fixation results, overall the increased prevalence rate used in the present study increased hit rate, and lowered RT and false alarm rate, relative to the prevalence level used in Chapter 2. The pattern of first fixations to targets and forthcoming targets was different across studies. In the present study, more targets were first fixated one step before onset at the target colour and fewer were first fixated post-onset at the target colour compared to Experiment 3 in Chapter 2, suggesting an effect of target prevalence upon search guidance. Furthermore, in the present study, targets first fixated one step before reaching the target colour received significantly faster post-onset responses than those targets first fixated post-onset.

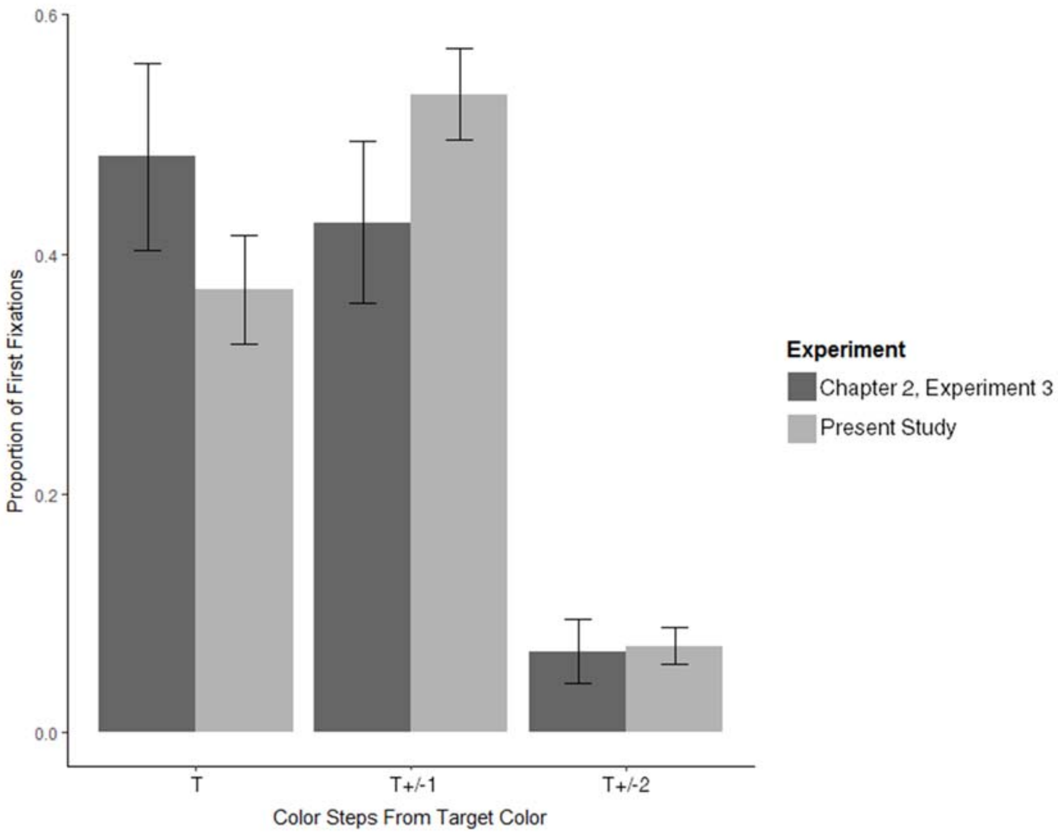

Figure 3.7. Proportion of first fixations to targets and forthcoming targets at 0, 1 and 2 colour steps from the target colour in both the present study and Experiment 3 in Chapter 2.

3.5.4 Individual Differences

The mean score on the IUS-12 was 27.20 (*SD* = 7.92) and the mean visual digit span score was 7.04 (*SD* = 1.62). While no comparison can be made for the digit span (due to using a different task), the IUS-12 data was similar to that observed in Chapter 2 (*M* = 28.72, *SD* = 9.96), *t*(56.69) = 0.63, *p* = .53. LMM analyses were performed in R (v3.4.0) using the lme4 package (v1.1-7; Bates, Mächler, Bolker, & Walker, 2014). These models allow analysis of these data and their interaction as continuous variables and, because they do not rely upon aggregated means, are more robust to missing data and outliers. All models included participant as a random factor. The aim of this analysis was to replicate previous findings linking IU and verbal WMC to behavioural performance and eye movements and, as such, model fitting began in all cases with a model containing the two-way interaction between IU and verbal WMC and iterated through more parsimonious variants until reaching the best-fitting model (any models that failed to converge were excluded). The effects of individual differences in verbal WMC and IU were considered in relation to a number of behavioural and eye movement measures. RT, fixation duration, number of fixations per trial and scanpath length were all analysed using standard LMMs. Hit rate, false alarm rate and an index of the extent predictive fixations to TPDs (calculated as the rate of first fixation of forthcoming targets at one step from the target colour compared to as targets post-onset) were analysed as binary variables using binomial generalized linear mixed models (GLMMs). See Table 3.2 for LMM results. The coefficients shown for the GLMM on hit rate in Table 3.2 are, as is standard for binomial GLMMs, in *logit* units. For interpretation in real terms, based on the coefficient of 0.04 for the effect of IU on hit rate, it was estimated that across the full range of observed IU scores, from 16 to 57, the probability of correctly hitting a target increased by 0.07. This effect, and its interaction with verbal WMC, are also shown in Figure 3.8. In summary, IU was found to be positively associated with hit rate and this effect was moderated by verbal WMC, such that the association between IU and hit rate was strongest in individuals with high verbal WMC.

Table 3.2

Generalised Linear Mixed Models and Linear Mixed Models Examining Individual Differences in Verbal WMC and IU at Baseline

	Hit Rate	Response Time	False Alarm Rate	Color Step From T At First Fixation	Scanpath Length	Number of Fixations	Fixation Duration
Constant	3.02*	7.36*	−2.92*	0.39*	782.40*	126.97*	5.46*
	(0.12)	(0.03)	(0.17)	(0.09)	(18.92)	(2.27)	(0.03)
IU	0.04*	-	-	-	-	-	-
	(0.02)						
Verbal WMC	−0.04	-	-	-	-	-	-
	(0.07)						
IU x Verbal WMC	0.02*	-	-	-	-	-	-
	(0.01)						
Observations	7,597	7,176	7,876	6,873	3,312	3,312	3,312
Log Likelihood	−1,578.79	−5,830.39	−2,002.89	−4,491.52	−20,728.40	−13,697.47	3,526.15
Akaike Inf. Crit.	3,167.58	11,666.79	4,009.79	8,987.03	41,462.80	27,400.94	−7,046.30
Bayesian Inf. Crit.	3,202.26	11,687.42	4,023.73	9,000.71	41,481.11	27,419.26	−7,027.99

Note: *p<0.05

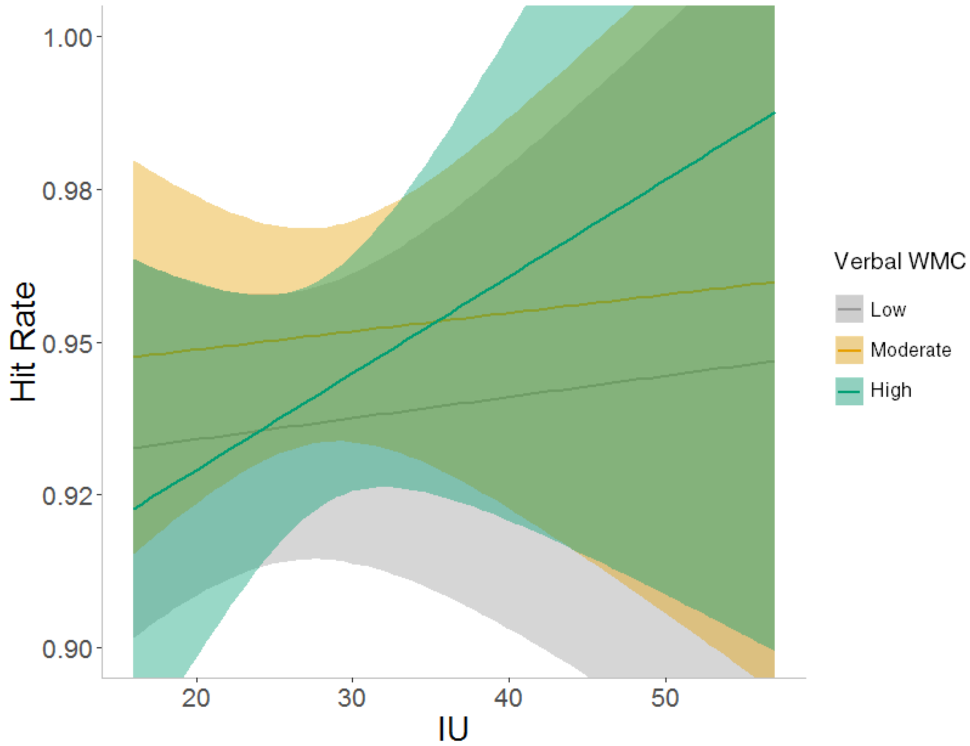

Figure 3.8. Hit rate and intolerance of uncertainty (IU) at low, moderate and high levels of verbal working memory capacity (WMC; shaded regions show continuous 95% CIs). Verbal WMC was split at the 33rd and 66th percentiles to give three categories. This categorization was only for the purposes of visualization and these data were included in all analyses as continuous data.

3.6 Working Memory Training Results

IU and VAS measures were analysed to check for baseline group and/or time differences. A between-subjects t-test indicated that there was no significant difference in IU between the two training groups, $t(19) = 1.34$, $p = .197$. An ANOVA was conducted for all VAS and included training group and time as factors. There was a main effect of group on the VAS ‘concentration’ item, $F(1,18) = 4.74$, $p = .043$, such that those who received active training reported better concentration (M = 109, SD = 21) than those who received control training (*M* = 90, *SD* = 19). However, there were no other significant main effects or interactions of group and time in terms of any other VAS measures, *Fs* $<=$ 4.33. These results show that groups did not differ in IU and that there was only a very limited group difference in mood.

3.6.1 Working Memory Training Performance

The training task performance of those who completed the adaptive WM training was considered in terms of the mean *n*-back level attained during a daily session. Analysis showed improvement in the active WM intervention group, with a significant increase between first (*M* = 2.04, *SD* = 0.56) and final training sessions (*M* = 2.83, *SD* = 0.85), $t(9)=3.42$, $p=.008$.

3.6.2 Visual Search Task

Data from the visual search task were analysed to examine the effects of WM training on basic behavioural and target prediction measures reported at baseline in the previous section. There was a significant effect of time upon hit rate, $F(18) = 17.82$, $p < .001$, $\eta 2G = 0.28$, RT, $F(18) = 68.88$, $p < .001$, $\eta 2G = 0.23$, and false alarm rate, $F(18) = 50.81$, $p = .001$, $\eta 2G = 0.13$, such that hit rate increased and false alarm rate and RT decreased. There were no significant effects of training group and no significant group by time interactions, Fs $<=$ 2.32. The interaction between group and time with regard to false alarm rate neared statistical significance, $F(18) = 3.67$, $p = .065$, $\eta 2G = 0.04$. The active training group had a higher false alarm rate pre-training than the control group, but this difference narrowed post-training (means are shown in Table 3.3).

To test the effects of WM training upon target prediction, a 2x2x3 (time x training group x colour step) ANOVA was conducted on the proportion of first fixations made to targets, TPDs at one and two steps from the target colour. The purpose of this analysis was to examine the effect of WM training on target prediction so only the two- and three-way interactions between time and colour step and time, colour step and training group were examined and none of these interactions were significant, Fs <=1.07.

Table 3.3

Mean Hit Rate, Response Time and False Alarm Rate in the Search Task.

	Control Training		Active Training	
	Pre-training	Post-training	Pre-training	Post-training
Hit Rate	0.94 (0.03)	0.97 (0.02)	0.93 (0.04)	0.97 (0.02)
Response Time (ms)	1,889 (299)	1,592 (310)	1,953 (410)	1,601 (250)
False Alarm Rate	0.05 (0.03)	0.03 (0.03)	0.10 (0.09)	0.04 (0.04)

Note. Standard deviations shown in parentheses

3.6.3 Working Memory Capacity and Attentional Control Tasks

The effects of time (pre- and post-training) and training group were considered with respect to performance in the digit span, change detection, ANT and antisaccade tasks. If the benefits of active training transfer to untrained tasks, this should be evident in a significant group by time interaction. There were no significant effects or interactions with respect to digit span, (*F*s <= 2.40).

In the change detection task, hit rate improved over time (*M* = 0.73, *SD* = 0.45 to *M* = 0.79, *SD* = 0.41), *F*(1,18)=9.42, *p* = .007, η^2_G = 0.13, and the effect of time upon RT also neared significance (*M* = 744 ms, *SD* = 124 to *M* = 678 ms, *SD* = 116), *F*(1,18) = 4.00, *p* = .061, η^2_G = 0.07. There were no other significant effects or interactions, *F*s <= 0.43. There were no significant effects or interactions in terms of accuracy or first saccade latency on antisaccade trials, *F*s <= 1.44. In the ANT, the alerting score improved over time from 42.91 (*SD* = 32.31) to 87.32 (*SD* = 42.91), *F*(1,18) = 4.97, *p* = .042, η^2_G = 0.04. There were no other significant effects or interactions, *F*s <= 2.26.

3.6.4 Summary of Working Memory Training Results

In summary, while there was some improvement in task performance post-training (hit rate increased and FA and RT rates decreased over time), there was no evidence that WM training differentially impacted on performance in the visual search task and no evidence that the effects of WM training generalised beyond performance in the n-back itself. Given these results, no examination of individual differences was conducted at the level of the training subgroups.

3.7 Transcranial Direct Current Stimulation Results

IU and VAS measures were analysed to check for baseline group and/or time differences. A between-subjects t-test indicated that there was no significant difference in IU between the two training groups, $t(25) = 0.03$, $p = .979$. An ANOVA was conducted for all VAS and included training group and time as factors. There was a group by time interaction for the VAS item that asked participants to rate how hard they tried, $F(1,23) = 8.36$, $p = .008$. In the active stimulation group, participants reported trying less hard during their first visit (*M* = 111, *SD* = 22), than during their second visit (*M* = 125, *SD* = 11), $t(12) = 3.21$, $p = .007$. No difference was observed in the sham stimulation group, $t(11) = 0.78$, $p = .455$. There were no other significant main effects or interactions of group and time in terms of any other VAS measures, $F <= 3.83$. These results show that groups did not differ in IU and there was no clear evidence of a difference in effort (beyond that attributable to active stimulation itself).

3.7.1 Visual Search Task

There was a significant effect of time upon hit rate, $F(24) = 11.49$, $p = .002$, $\eta^2_G = 0.12$, RT, $F(24) = 22.09$, $p < .001$, $\eta^2_G = 0.10$, and false alarm rate, $F(24) = 13$, $p = .009$, $\eta^2_G = 0.13$, such that all three improved post-stimulation. There were no significant effects of stimulation group and no significant group by time interactions, *F*s <= 1.23. Means are shown in Table 3.4.

A 2x3x3 (time x training group x colour step) ANOVA was carried out, this time to assess the impact of tDCS upon target prediction. Again, only the two- and three-way interactions between time and colour step and time, colour step and stimulation group and were examined and none of these interactions were significant, *F*s <=0.98. Again, the pattern of data did not differ significantly from that shown in Figure 3.7.

Table 3.4

Mean Hit Rate, Response Time (RT) and False Alarm Rate in the Visual Search Task and Hit Rate in the Change Detection Task (CDT) by Stimulation Group and Time

	Sham Stimulation		Active Stimulation	
	Pre- stimulation	Post- stimulation	Pre- stimulation	Post- stimulation
Hit Rate	0.94 (0.03)	0.97 (0.03)	0.96 (0.04)	0.98 (0.01)
RT (ms)	1,934 (387)	1,670 (353)	1,691 (274)	1,516 (236)
False Alarm Rate	0.07 (0.06)	0.04 (0.03)	0.09 (0.11)	0.03 (0.03)
CDT Hit Rate	0.69 (0.10)	0.77 (0.08)	0.72 (0.14)	0.76 (0.11)

Note. Standard deviations shown in parentheses

3.7.2 Working Memory Capacity and Attentional Control Tasks

The effects of time (pre- and post-stimulation) and training group were considered with regard to performance in the digit span, change detection, ANT and ant saccade tasks. Similarly to the effects of WM training, if the benefits of active, relative to sham, stimulation generalize to these tasks then this should be evident in a significant group by time interaction. Digit span improved over time from 6.85 (*SD* = 1.62) to 7.42 (*SD* =

1.42), $F(1,24) = 9.26$, $p = .006$, $\eta^2_G = 0.02$, but there was no significant effect of group and no significant interaction with time, *Fs* <= 0.38.

In the change detection task there were significant improvements in hit rate, $F(1,24) = 32.02$, $p < .001$, $\eta^2_G = 0.07$, and RT, $F(1,24) = 8.90$, $p = .006$, $\eta^2_G = 0.08$, over time. There was also a significant interaction between group and time in their effect on hit rate in this task, $F(1,24) = 4.59$, $p = .042$, $\eta^2_G = 0.01$. Pairwise comparisons revealed that both the control group, $t(12) = 5.84$, $p < .001$, and the experimental group, $t(12) = 2.36$, $p = .036$, improved over time. The means (see Table 3.4) show that this interaction was driven by a greater improvement over time in the sham stimulation group relative to the active group, indicating that this interaction does not represent a benefit of active stimulation.

There were no significant effects or interactions in terms of accuracy or first saccade latency on antisaccade trials in the antisaccade task, Fs <= 1.43. There were also no significant effects or interactions in terms of the altering, orienting or executive control networks in the ANT, *F*s <= 1.86.

3.7.2 Summary of Transcranial Direct Current Stimulation Results

In summary, there was no indication that active anodal tDCS of the left DLPFC provided a specific benefit relative to sham stimulation in the visual search task, or indeed any of the other tasks participants performed. Performance tended to improve over time on most tasks. Again, given these results, no examination of individual differences was conducted at the level of the stimulation subgroups.

3.8 General Discussion

The goals of the present study were threefold: (1) to replicate and extend previous findings relating to target detection and prediction in conditions of high target prevalence; (2) to confirm the roles of individual differences in IU and verbal WMC in predicting false alarm rate and eye movements in a dynamic search task; (3) to assess the efficacy of WM training and tDCS of the left DLPFC in improving performance in a dynamic search task and cognitive processing more generally.

The first of these goals was addressed by examining basic performance and eye movements from the dynamic search task in the context of previous work. It was found that the higher level of target prevalence in the present study led to a higher hit rate, faster RTs and a lower false alarm rate compared with Experiment 3 in Chapter 2 where target prevalence was low. These basic behavioural performance improvements are consistent with the well-established effect of target prevalence on the criterion used for the perceptual identification of targets (Godwin, Menneer, et al., 2014). The present study also found a novel effect of target prevalence on target prediction. Specifically, the higher level of target prevalence in the present study increased predictive first fixations to TPDs and supported faster RTs for targets first fixated predictively. It is suggested that high target prevalence increases the validity of TPDs as cues to target onsets, facilitating predictive behaviour and allowing for speeded responses to predicted targets, in a way that was not possible in low target prevalence conditions. Furthermore, whatever the extent of the criterion shift due to the increased prevalence level, it did not result in premature responses or an inability to utilize the cues provided by TPDs.

The second goal of the present study was to confirm previously observed roles of IU and verbal WMC as predictors of dynamic visual search performance. A Signal Detection Theory analysis was not possible in the present case, however, SDT provides a clear theoretical framework that can be used to conceptualize these results and relevant terminology is used accordingly. In the present study, IU was found to be positively associated with hit rate in the search task and this effect was moderated by verbal WMC, such that the association between IU and hit rate was strongest in individuals with high verbal WMC. In contrast, previous research showed that individuals who reported increased symptoms of IU were more likely to identify non-targets as targets (there was a positive association with false alarm rate) and this relationship was moderated by verbal WMC, such that it was strongest in individuals with low verbal WMC. The shift in the effect of IU (and its interaction with verbal WMC) from false alarm rate to hit rate is explained in terms of the higher level of target prevalence used in the present study and the apparent influence of IU upon response criterion.

In both the present and previous studies, the findings indicate that WMC is important in ensuring that IU does not have a deleterious effect upon behavioural performance. In Chapter 2, the cost of high IU to false alarm rate was driven primarily by individuals with low verbal WMC and, similarly, in the present study, the benefit of high IU to hit rate was driven primarily by individuals with high verbal WMC. In the terms of Signal Detection Theory, these results are consistent with an effect of verbal WMC on perceptual sensitivity. An increase in sensitivity, associated with high verbal WMC, would allow targets to be more reliably discriminated from distractors, and could improve hit rate with no effect on false alarm rate (i.e., if the 'signal' distribution was further separated from the 'noise' distribution). Similarly, a decrease in sensitivity, associated with low verbal WMC, would mean that targets and distractors were less easily discriminated, and false alarm rate could be increased with no effect on hit rate (i.e., if the 'noise' distribution overlapped more with the 'signal' distribution). This account is illustrated in Figure 3.9 using hypothetical 'signal' and 'noise' distributions that are consistent with our findings.

Figure 3.9a illustrates the impact criterion shift associated with IU, Figure 3.9b shows a change in perceptual sensitivity associated with verbal WMC and Figure 3.9c combines these two effects.

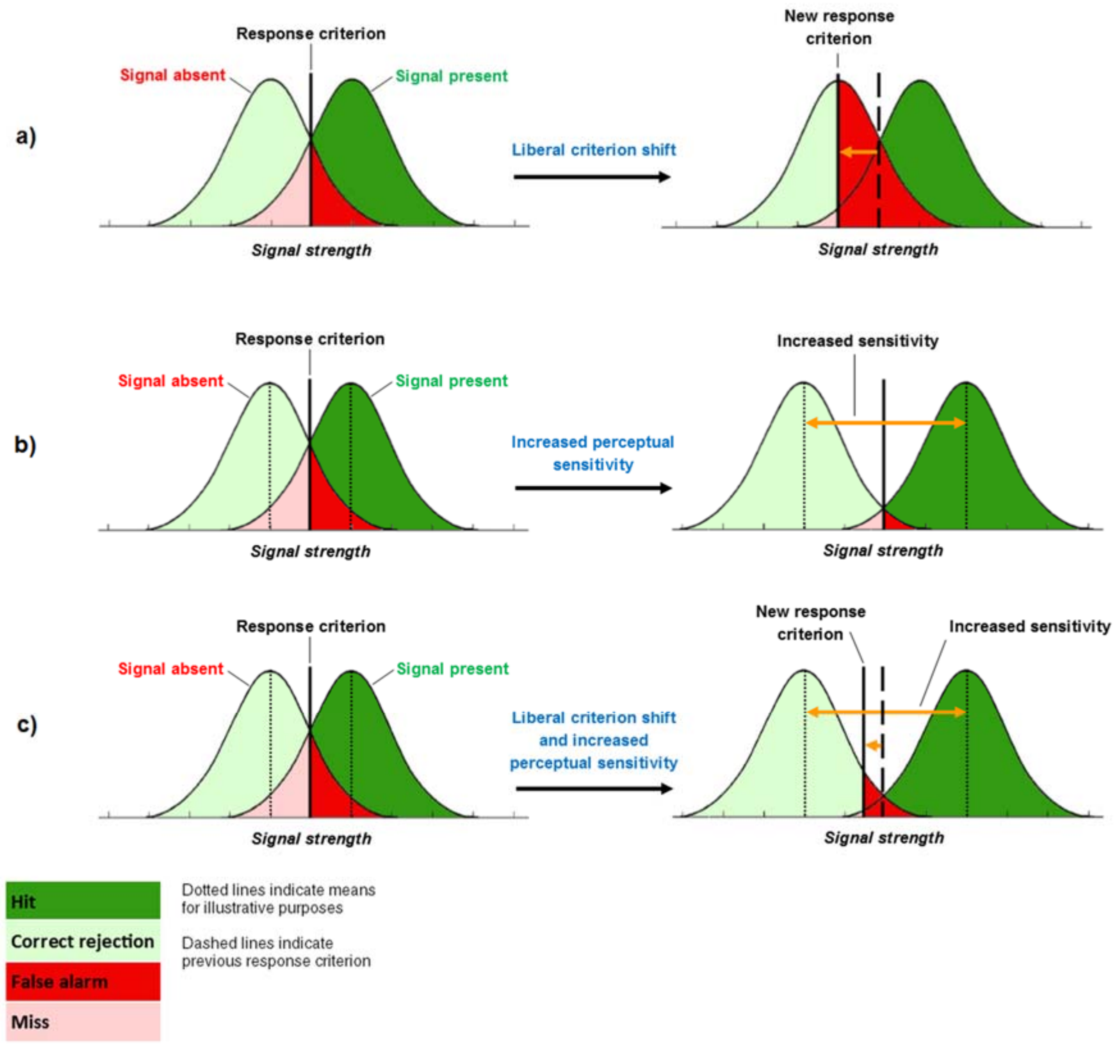

Figure 3.9 Hypothetical signal and noise distributions illustrating: (a) the effect of a shift in response criterion; (b) the effect of increased perceptual sensitivity; and (c) the combined effect of a criterion shift and increased sensitivity.

This account is supported by previous literature which links WM to perceptual sensitivity. For example, one study found that WMC mediated the effects of externalizing mental health disorders on sensitivity in a go/no-go learning task (Endres, Rickert, Bogg, Lucas, & Finn, 2011) and another found that high WMC individuals demonstrated greater sensitivity than low WMC individuals when judging time intervals (Broadway & Engle, 2011). Of particular note is Unsworth and Engle's (2007) framework for individual differences in WMC, which states that low WMC individuals typically experience greater interference from irrelevant information due to a reduced ability to discriminate this from relevant information and an increased reliance upon external cues to guide attention. Furthermore, in a series of perceptual identification experiments, Soto, Wriglesworth, Bahrami-Balani and Humphreys (2010) found that cues held in WM significantly improved sensitivity. They also found that verbal cues were as effective as visual cues and suggest that the conceptual match between a verbal cue and a visual target is sufficient for this boost to sensitivity. In terms of the present study, this is consistent with an account where participants used self-assigned verbal labels to improve their discrimination of targets from target-similar colours.

In addressing the third goal, the present study examined the effects of both a program of dual *n*-back WM training and tDCS of the DLPFC upon performance in the complex search task and, to check for a range of other specific effects, a set of WM and attention tasks. Improvements in the active training and stimulation groups (relative to controls) were predicted across all tasks, but the only reliable effects were those of practice (improvements over time). There are a number of possible explanations for the lack of observed effects here and some of these will be considered with respect to each intervention in turn.

The literature on WM training is mixed and a number of recent reviews have highlighted limitations in the reliability of the distant transfer of training in particular (Harrison et al., 2013; Melby-Lervåg & Hulme, 2015b; Shipstead, Redick, & Engle, 2012). A lack of standardised and reliable training protocols, including adequate controls and validated schedules, may be responsible for the inconsistent results in the literature

(Morrison & Chein, 2011) and, in light of this, the present study used an established dual *n*-back training program (Max Owens et al., 2013). Despite the mixed literature, it is difficult to ignore previous findings that suggest generalized improvements to fluid intelligence following training and more widely replicated near transfer effects (Au et al., 2014, 2015; Greenwood & Parasuraman, 2016; Jaeggi et al., 2008). If the present results had indicated a lack of transfer to the visual search task in the presence of a range of near transfer effects on the other WM and attention tasks, then one might reasonably explore explanations for the lack of far transfer that assumed a basic, if limited, level of training effectiveness, for example, underlying individual differences in neuroanatomy (Simon, Skinner, & Ziegler, 2016). However, the lack of any training effects, even in basic WM tasks, suggests a more fundamental explanation.

One possibility is an insufficient sample size. The working memory training intervention in the present study involved 20 participants. This is actually greater than the mean number of participants (19.96) across the 20 studies reviewed by Au et al. (2014, 2015) in their meta-analyses which found significant far transfer effects. This suggests that, in itself, a small sample cannot fully explain the present null results. One related issue may be a lack of engagement with the training task amongst participants. Training performance was monitored to ensure that participants completed the training according to the correct schedule and that their performance did not fall to a floor level. However, given that participants completed the training in their own time in a location of their choosing, it is very difficult to be certain that participants engaged with the task fully and as instructed. Also, while participants were kept blind to their group assignment, given the training schedule, the availability of information regarding WM training available online and the sample of undergraduates, it would be surprising if all participants remained blind to their group assignment and the proposed mechanisms of action behind the training.

The tDCS intervention produced a similar set of null results, with no reliable benefit of active stimulation observed in the visual search task or the other WM or attention tasks. Similarly to the WM training results, the fact that tDCS was found to have no effect upon the search task or the WM and attention task suggests a more fundamental explanation. One such explanation, in the context of the present experimental method, is the timing and duration of the tasks following stimulation. The visual search task had the longest duration and was completed immediately following stimulation, the other WM and attention tasks were completed after this. Changes in cortical excitability have been shown to persist for 1.5 hours following stimulation at 1mA for 13 minutes (Nitsche & Paulus, 2001), a weaker current and a shorter duration than the stimulation delivered in the present study. However, the effects of stimulation do diminish over time and one would reasonably expect a reduced likelihood of observing any significant effects of stimulation in tasks performed towards the end of a testing session compared to the beginning.

Early tDCS research established clear directional predictions about the excitatory and inhibitory effects of anodal and cathodal stimulation respectively (Nitsche & Paulus, 2000). However, as tDCS has been applied to a greater range of brain regions and with different electrode configurations, it has become clear that its effects cannot be so clearly distinguished and that results may be influenced by: the present state of underlying networks; inter-individual differences; and, in uni-lateral montages, the interhemispheric balance of activity (Fecteau, Knoch, et al., 2007; Tremblay et al., 2014). Two recent reviews by the same groups of authors, one examining 117 studies and the other 198 studies, have even suggested that single-session tDCS has no reliable effect upon cognitive performance (Horvath, Forte, & Carter, 2015a, 2015b), although this may be attributable to issues with inter-subject variability (Horvath, Carter, & Forte, 2014) and the resting brain state dependency of stimulation effects (Silvanto et al., 2008).

The present study supports and extends previous findings obtained from the same dynamic colour search task. Relative to previous work, higher target prevalence was found to improve performance and facilitate the speeded predictive detection of targets, which represents a novel type of prevalence effect. It is suggested that a higher level of target prevalence increased the validity of target predictive distractors as cues to forthcoming target onsets. Increased target prevalence also affected the relationship between individual differences in IU (including its interaction with verbal WMC) and target detection, with an effect being observed in terms of hit rate rather than false alarm rate. An account of these findings is provided in terms of a criterion shift, driven by IU, and a change in perceptual sensitivity, driven by verbal WMC. Neither the WM training or tDCS interventions were effective in improving performance in the search task or other measures of WMC and attentional control. However, this is not to say that these null results were uninformative, and they provide useful methodological considerations for the application of WM training and tDCS in future studies of complex visuo-cognitive tasks. In addition to the proposed theoretical account of the effects of IU and verbal WMC, the pattern of results around these specific individual factors has significant practical implications for real-world visual monitoring tasks. When selecting personnel for such tasks, IU and verbal WMC represent characteristics that could be used to identify individuals who are likely to perform well at given levels of target prevalence.

Chapter 4

Searching for Two Categories of Target in Dynamic Visual Displays Reduces Monitoring Ability

4.a Abstract

Monitoring dynamically changing displays for targets can involve both post-onset and predictive target detection. Consistent with dual-target and task switching costs, predictive monitoring for one target category may be impaired by monitoring for a second, however, this cost could be reduced in particular display configurations. Participants searched dynamically changing displays of squares and numbers for colour and/or number targets. Stimuli were presented in contiguous or discrete spatial configurations, which involved smaller attentional shifts but increased visual clutter, or reduced clutter but larger attentional shifts respectively. A dual-target cost was found to target detection speed and predictive monitoring and, in single-target conditions, the proximity of distractors reduced predictive monitoring. The need to store and switch between specific target templates appears to be associated with reduced capacity for using broad templates to predictively detect targets. There are implications for real-world visual tasks that involve multiple target categories and for electronic display design.

4.b Publication Note

This chapter is under review at Applied Cognitive Psychology.

4.1 Introduction

Many studies have explored visual search for multiple targets defined within a single category, for example, two different colours (e.g., Menneer et al., 2008). Understanding how this impacts search is important, especially in the context of real-world visual scenarios that are at least partially reducible to looking for specific colours that indicate target presence. An example of this is the search of geological imaging, where blue indicates background sandstone and red indicates valuable, hydrocarbon-rich, shale deposits (Donnelly et al., 2006). However, real-world search tasks often involve targets that are defined across multiple different categories, for example, colour and numerical indicators in a vehicle control system or head-mounted display. In these scenarios, different categories of information are also typically displayed in different locations on specific dials or screens. Detecting these different categories of target therefore requires both the executive control of attention to switch between different locations and visual search processes that are calibrated for each category of target. The present study attempts to capture the processes involved in searching for targets within dynamic displays by exploring search for two different categories of target and the impact of having to shift attention between two stimulus sets, presented in either spatially contiguous or discrete display configurations.

Previous studies of dual-target search, where targets were defined within a single category, have found a 'dual-target cost' to response time, accuracy and search guidance (Menneer et al., 2004; Stroud et al., 2012, 2011). Simultaneously searching for two categories of target involves more diverse task sets and can be thought of as a special case of task switching. While the overall task remains one of visual search, the search system must be reconfigured in order to detect different target categories. Switching between two tasks incurs performance costs that arise from residual activation of previously active task sets, and the need to reconfigure target templates and stimulus-response mappings (Meiran, 2000; Meiran, Chorev, & Sapir, 2000; Pashler, 2000). These costs can sometimes be reduced if there is time to prepare for a switch and if there is no overlap in stimulus-response mappings between tasks (Kiesel et al., 2010; Ravizza & Carter, 2008).

In the searches involved in the complex real-world tasks described above, where stimuli change state dynamically over time, effective target detection requires continuous monitoring. This is in addition to the need to switch between stimulus sets when there are two target categories present in displays. When stimuli change state and these changes exhibit contingencies over time, target detection may be aided by focused monitoring on a subset of distractor identities that might soon become targets. For example, in a heatmap that is coded according to a psychologically ordered colour space, the onset of a red target might be preceded by the onset of an orange distractor. Chapter 2 explored the monitoring of target predictive distractors in a task where participants searched for the onset of a colour target in a set of dynamically changing colour stimuli. Evidence of predictive monitoring was found when items made single step colour changes through a psychologically ordered colour space and, as target predictive distractors approached a target state, they were fixated more than background items. This was a strategy that all participants engaged in and facilitated the identification of potential targets compared to when conditions prevented predictive monitoring. However, predictive monitoring was characterized by two specific types of error: (1) false alarms arising from premature responses to forthcoming targets and (2) misses after fixating a forthcoming target but not returning to it post-onset. It is important to note that while these specific types of error occurred during predictive monitoring, there was no evidence that suggested it represented an inferior strategy. The critical questions explored in the present study are whether predictive monitoring is maintained when participants must also simultaneously monitor for targets drawn from a different category and how this is influenced by a manipulation of spatial configuration.

Predictive monitoring may provide a number of advantages when searching for targets across categories. First, predictive monitoring could provide a useful mechanism to reduce the size of the set of items to be checked and re-checked. Second, a target-predictive distractor that may soon become a target might act as a signal to maintain attention on the current stimulus set rather than switching to the alternate set. Third, the absence of target-predictive distractors might conversely serve as a signal to switch attention to the alternate set. It remains a possibility, however, that the cognitive load associated with managing the search for two targets from different categories might eliminate or reduce the ability to monitor predictively.

If it is possible to predictively monitor for targets from multiple categories, there may be spatial constraints that limit its effectiveness. A simple manipulation of the spatial constraints is to position stimulus sets so that they appear in a single contiguous configuration or in spatially discrete (i.e., separate) locations. It is possible that the proximity of the two stimulus sets in spatially contiguous displays will facilitate predictive monitoring across categories. This might be the case if fewer large overt shifts of attention are required and more stimuli can be monitored in parallel. However, the increased visual clutter of a contiguous display may impair monitoring (Lavie, 2006; Lavie, Beck, & Konstantinou, 2014) and increase distractor interference.

The present study used a dynamic dual visual search and monitoring task to explore how the ability to prioritize likely target locations was affected by the need to simultaneously monitor for the onset of a target from a second category. This task was a development of the colour search task used in Chapters 2 and 3. Colour and number targets were chosen due to their different features, such that any attribute supporting attentional guidance to colour targets would be independent of any supporting guidance to the number targets. All stimuli were presented in arrays where each stimulus changed dynamically according to single steps along predefined ordered scales in colour and number space. Dual-target search and both types of single-target search were examined in each display configuration. Target detection was measured in terms of behavioural measures of hit rate, response time (RT) and false alarm rate. Eye movements were used to assess the ability to prioritize and monitor potential targets. This was accomplished by examining first fixations to targets and forthcoming targets (as a function of the number of colour or number steps from a target state) and the duration of visits to each stimulus array.

In the particular form of contiguous display used in the present study, the number set was embedded within the colour set. This configuration placed the centre of each stimulus set in the same location, such that fixed monitoring from this region placed the number set in foveal vision and the colour set further into the periphery. The contiguous configuration was contrasted with a spatially discrete display configuration where the colour and number sets were located on opposing sides of the display (see Figure 4.1a). The two spatial configurations contrasted in many display parameters (e.g., clutter, spatial extent, necessity for shifts of spatial attention, the implicit prioritization given to one stimulus set over another). However, any effects of task on predictive monitoring that did not interact with display configuration were likely to be robust across other display configurations. Furthermore, although both colour and number targets were considered here, there were differences between the stimulus arrays in terms of visual size, set size and the number of potential distractor identities. The properties of the number set (i.e., their overall size and number of items) were defined to fit within a contiguous array with the colour set, while maintaining discriminability. No attempt was made to maintain equivalence between the two stimulus sets in these respects and, accordingly, the colour and number searches were not treated equally. From an applied perspective, this was representative of many visual scenarios where one stimulus set provides richer and more complex information than another, for example, the view of an external environment through a head mounted display.

Based on previous studies of dual-target visual search, it was predicted that target detection would be worse, and predictive monitoring more difficult, when monitoring for both targets relative to a single target type. It was expected that this would be evident in a reduced hit rate, elevated RTs, and fewer predictive first fixations to forthcoming targets in dual-target, relative to single-target, conditions. Where predictive monitoring was possible, it was expected that there would be evidence of false alarms (premature responses) and misses. With regard to the effects of display configuration, it was anticipated that discrete displays would facilitate single-target searches due to the reduced likelihood of distraction, but that contiguous displays would facilitate dual-target searches due to the reduced need for large, overt, shifts of attention.

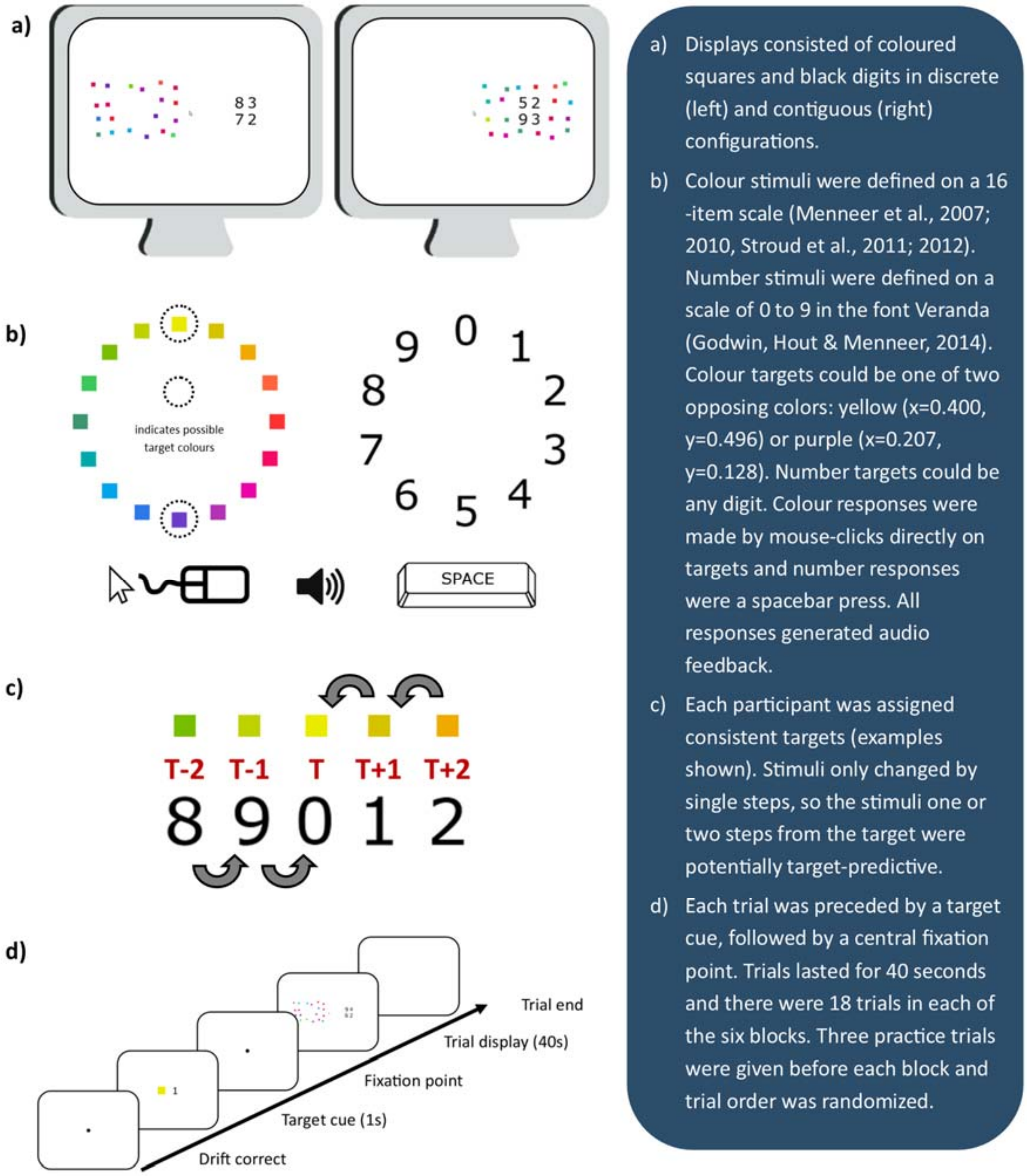

Figure 4.1. Method infographic.

4.2 Method

4.2.1 Participants

26 participants (age range = 19 to 42 years, *M* = 25.0 years, *SD* = 5.4, 14 female) took part in the study. All were students at the University of Southampton and participated

for partial fulfilment of a course requirement or were compensated with £12. Participants had normal visual acuity (>= 1.0 decimal at 70 cm), tested using the Freiburg Visual Acuity Test (FrACT; Bach, 1996), and normal colour vision, tested using the City University Colour Vision Test 3rd Edition (Fletcher, 1998).

4.2.2 Apparatus

Stimuli were displayed on a 21" CRT with a resolution of 1,024 x 768 pixels and a refresh rate of 120 Hz. This was controlled using a computer connected to an SR Research EyeLink 1000 eye-tracker, operating at a sampling rate of 1,000 Hz. A nine-point calibration was used and was accepted only when none of the points had an error of more than 0.5° of visual angle. Participants were seated 70 cm from the display and, using a chin rest, viewed the display binocularly, although only the right eye was tracked. The experiment was programmed using SR Research Experiment Builder with additional code in Python. Participants responded using a Viglen USB keyboard and optical mouse.

4.2.3 Design and Procedure

A display configuration (contiguous, discrete) by search target (single-target colour, single-target number, dual-target) within-participants design resulted in six blocked and counterbalanced conditions. The side of the display on which the numbers appeared was counterbalanced between participants but remained constant for each participant. Participants were asked to search for a particular colour target, a particular number target, or both targets. In single-target blocks there were six target absent trials, six single-target trials and six two target trials. In dual-target blocks there were two trials with each of the nine combinations of zero, one and two of both types of target. Twelve minutes of eye movement data were generated for each block. See Figure 4.1 for details of trial procedure and responses.

4.2.4 Stimuli

In contiguous configurations, four digits were located within a rectangular array of 20 coloured squares. This was centred at a point 7.29° left or right of the display centre. In discrete configurations, the digit and square arrays were similarly centred on opposing sides. Squares, each 0.57° x 0.57°, were in irregular 6x4 arrays with the central four stimuli removed. Squares never abutted and each appeared randomly offset within an area of 2.15° x 2.15° which was used to code fixations. The maximum size of the colour array was 11.61° x 7.35°. Number stimuli were displayed in a regular 2 x 2 array, with each digit no more than 1.08° x 1.14°. The maximum size of the number array was 2.79° x 3.77°. All of the above angles are visual angles calculated from the centre of the display.

Two colours and all numbers were used as targets. Each participant was assigned a colour target and a number target and these were counterbalanced between participants. When distractors were within two steps of a target, for both colours and numbers, they potentially predicted a forthcoming target onset and were considered to be target-predictive distractors (TPDs). Examination of whether targets were first fixated as TPDs forms the basis of later analysis of target monitoring. Within the colour array, there were four potential locations for targets or TPDs. These were varied trial-by-trial, were never allowed to abut and never included the four stimuli above or below the centre. As there were up to two colour targets per trial, at least two TPDs never reached the target colour but reached a final state one step from the target colour. Within the number array, any three out of four locations could become a target or TPD and, as there were up to two targets per trial, at least one TPD never reached the target number but reached a final state one step from the target number. Targets and TPDs would reset to a distractor state if a response was made or after a varied delay (see below). All stimuli changed in single sequential steps through

16 colours or 10 digits. Only one of each target type could be active at any time. See Figure 4.1 for further details of stimuli.

The colour stimuli were all approximately equally spaced in colour space and, with the exception of looping between ‘0’ and ‘9’, the numbers were equally semantically spaced (i.e., on a number line). While visual similarity has been shown to be a source of interference in search for numerical digits (Godwin, Hout, & Menneer, 2014), the semantic properties of numerical digits have been shown to provide strong guidance even when other factors are controlled for (Sobel, Puri, & Hogan, 2014) and the looping numerical scale provided a semantic context that was not matched in terms of visual similarity.

Stimulus arrays were updated dynamically with irregular refresh rates (M = 6.62 Hz, SD = 0.15). With no targets or TPDs present, distractors varied independently between the remaining 11 distractor colours and 5 distractor numbers. With every refresh, any stimulus could remain unchanged (0.6 probability), become more target-similar by one step (0.2 probability) or become less target-similar by one step (0.2 probability). The exception to this was when a distractor reached a point one step from a state reserved for targets or TPDs, and in such cases a distractor could only change to become less target-similar. This resulted in a mean rate of change of 2.02 Hz (SD = 0.54) for each distractor item.

The behaviour of targets and TPDs was determined by a number of properties: (1) a time before a distractor began changing towards a target state; (2) a time before which a distractor became a target; and (3) a time for which a target remained present before reverting to a distractor if not detected. These timers were not defined as such but were implemented as randomly generated counters that were incrementally reduced until reaching zero (when the corresponding event would occur). In practice, the first colour TPD became active after a mean of 6,566 ms (SD = 2,394), the first number TPD became active after a mean of 6,305 ms (*SD* = 2,440), the first colour target onset after a mean of 18,169 ms (*SD* = 6,453), the first number target onset after a mean of 16,222 ms (*SD* = 5,526), the second colour target onset (where applicable) after a mean of 25,200 ms (*SD* = 5,018) and the second number target onset (where applicable) after a mean of 22,319 ms (*SD* = 4,496). The mean duration of colour targets was 7,649 ms (*SD* = 3,099) and the mean duration of number targets was 7,520 ms (*SD* = 2,710), including durations shortened by responses. The specific parameters for the onset of targets were chosen so that no target would appear early after the beginning of a trial and not too late to allow monitoring.

4.3 Results

4.3.1 Analyses and Exclusions

To normalize distributions, all proportional data, including hit and false alarm (FA) rates, were arcsine-square-root transformed. Similarly, RT and visit duration data were log transformed. Untransformed means and standard deviations are reported. In the eye movement data, fixations were excluded from duration analyses if they were longer than 1,200 ms or shorter than 80 ms in duration or if they corresponded with a manual response (6.15% of all fixations).

4.3.2 Behavioural Analyses

The behavioural data were analysed using 2 (target: single-target, dual-target) x 2 (display configuration: contiguous, discrete) ANOVAs. Single-target colour and number searches were compared against responses to the matching target type from the dual-target conditions. Colour and number search were analysed separately in all cases.

Hit rates were near ceiling for colour targets (*M* = 0.97, *SD* = 0.04) and at ceiling for number targets, so no analyses of hit rates are presented. Response times and false alarm rates are shown in Figure 4.2. There were significant main effects of target on RT for colour, $F(1,25) = 17.57$, $p < .001$, $\eta^2_G = 0.08$, and number targets, $F(1,25) = 162.23$, $p < .001$, $\eta^2_G = 0.50$. In both cases, responses were faster in single-target than dual-target conditions. The main effect of stimulus configuration failed to reach significance for responses to either colour, $F(1,25) = 2.95$, $p = 0.098$, $\eta^2_G = 0.01$, or number targets, $F(1,25) = 2.27$, $p = 0.14$, $\eta^2_G = 0.01$). The interaction between target and stimulus configuration did not reach significance for either colour or number targets, $F(1,25) <= 3.44$. There were no significant main effects of target or stimulus configuration upon false alarm rate (all $F < 1.92$). These data support the predicted dual-target cost, relative to single-target searches, in terms of RT. This cost was not influenced by display configuration.

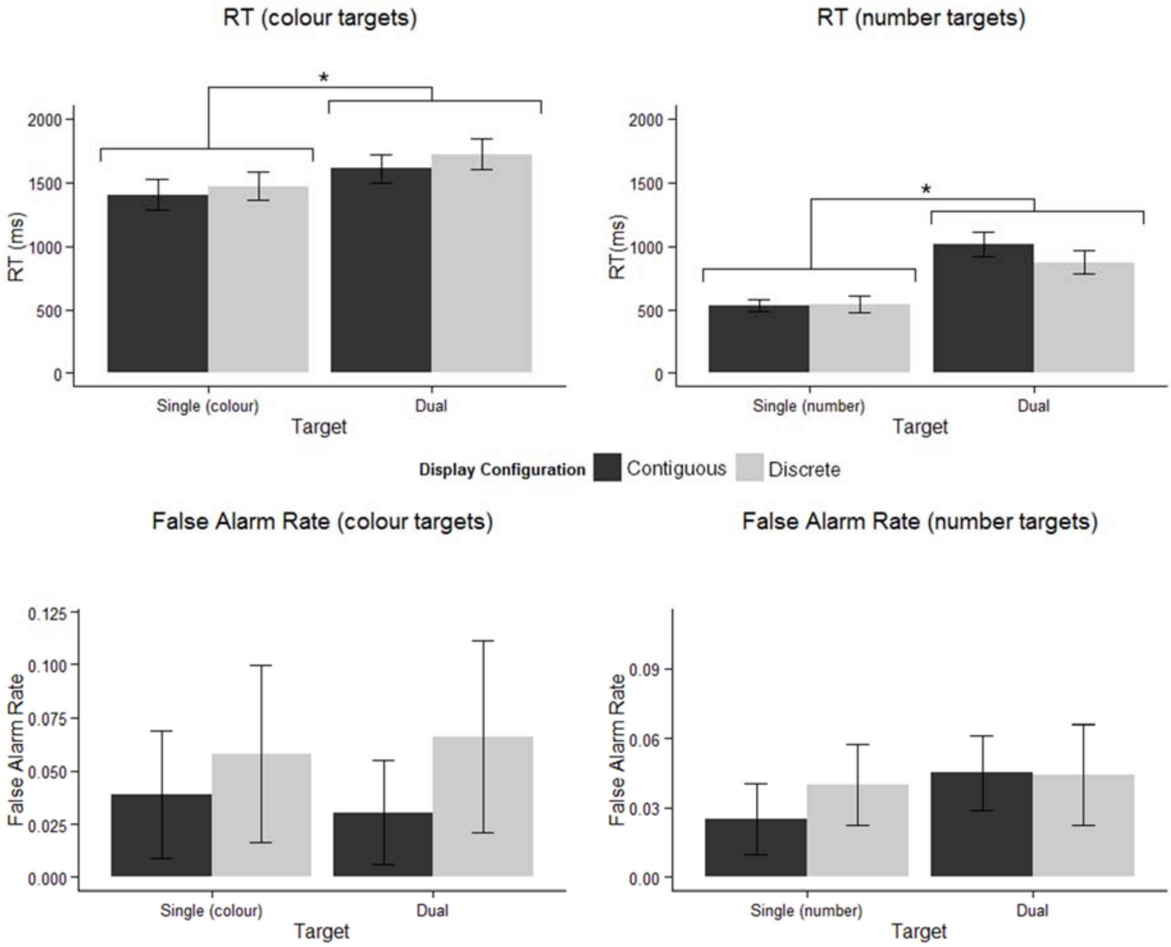

Figure 4.2. RTs (response times) and false alarm rates for all target types in all display configurations (error bars show 95% CIs and '*' indicates a pairwise comparison where p < .05).

4.3.3 Eye Movement Analyses

Visits were defined as groups of consecutive fixations made to either stimulus array. Visit durations for each array in each condition are shown in Figure 4.3. When monitoring for a single target type, discrete displays led to longer visit durations to the relevant stimulus array for both colour, $t(25) = 23.04$, p < .001, and number searches, $t(25) = 2.76$, $p = .011$, relative to contiguous displays. Longer visits were made to the irrelevant number region when monitoring for only colour targets in contiguous displays, $t(22) = 7.71$, $p < .001$, relative to discrete displays. There was no comparable effect when monitoring only for numbers, $t(18) = 1.11$, $p < .281$. These effects are consistent with the basic predictions made regarding the effects of display configuration on eye movements in single-target searches and confirm that contiguous displays led to longer visits to the relevant stimulus array.

When monitoring for both target types, consistent with predictions, visit durations to the number stimuli were longer in contiguous compared to discrete displays, $t(25) = 5.45$, $p < .001$. However, visit durations to the colour stimuli were longer in discrete compared to contiguous displays, $t(25) = 5.27$, $p < .001$, suggesting prioritization of, or difficulty disengaging from, the colour array. The pattern of visit durations to the colour array when monitoring for colour targets in contiguous displays was more similar to that observed in dual-target search (in either display configuration) than it was to colour search in discrete displays. This suggests that, in these circumstances, prioritizing colour stimuli is more challenging.

To examine the predictive monitoring of potential targets, first fixations to targets and TPDs that went on to receive a response were analysed (see Figure 4.4). It was reasoned that if a greater proportion of first fixations was made to TPDs than was made to targets post-onset, then this would provide strong evidence of predictive monitoring. The proportion of first fixations made to colour and number stimuli in these different states was analysed in two separate 3 (steps from target: T, TPD +/- 1, TPD +/- 2) x 2 (target: single-target, dual-target) x 2 (display configuration: contiguous, discrete) ANOVAs. The proportion of first fixations was defined as the proportion of all first fixations to stimuli that eventually became targets in the relevant category (or categories) in each condition.

With regard to first fixations of colour targets, the main effects of step, $F(2,50) = 139.11$, $p < .001$, $\eta^2_G = .68$, were significant, but the effects of target, $F(1,25) = 2.07$, $p = .162$, and display configuration were not, $F(1,25) = .04$, $p = .850$. The two-way interaction between target and step was significant, $F(2,50) = 27.07$, $p < .001$, $\eta^2_G = .12$, but the remaining interactions were not, $F <= 1.81$, $p => .174$. Post-hoc comparisons revealed that when monitoring for both target types compared to only colours a significantly greater proportion of colour targets were first fixated at T, $t(25) = 6.62$, $p < .001$ and a significantly smaller proportion of colour targets were first fixated at T+/-2, $t(25) = 5.12$, $p < .001$. There was no difference for those first fixated at T+/-1, $t(25) = 1.50$, $p = .147$. Analysis of fixations and refixations to colour targets and TPDs, which reflect monitoring over time, showed a mean of 1.52 (*SD* = 0.43) fixations was made to targets, and 4.84 (*SD* = 1.28) and 1.26 (*SD* = 0.12) total fixations to TPDs one and two steps from the target colour respectively. Background distractors at each of the remaining six steps from the target colour received an average of 1.57 (*SD* = 0.18) fixations.

The effect of predicting forthcoming colour targets was explored with respect to RT and false alarm rate for targets first fixated at T compared to those first fixated as TPDs at T +/- 1 (these data are shown in Figure 4.5). As with the basic behavioural analysis hit rates were again near ceiling and were not analysed. There was no significant difference in RT between colour targets first fixated as TPDs at T +/- 1 and those first fixated at T for: (1) colour search in contiguous displays, $t(25) = .07$, $p = .941$; (2) colour search in discrete displays, $t(25) = .94$, $p = .354$; (3) dual-target search in contiguous displays, $t(24) = 1.19$, $p = .245$; and (4) dual-target search in discrete displays, $t(25) = .32$, $p = .753$. The false alarm rate for stimuli first fixated as TPDs at T +/- 1 was significantly greater than zero for: (1) colour search in discrete displays, $t(25) = 2.70$, $p = .012$; (2) dual-target search in contiguous displays, $t(25) = 2.39$, $p = .025$; and (3) dual-target search in discrete displays, $t(25) = 2.56$, $p = .017$. However, the false alarm rate for colour stimuli first fixated as TPDs at T +/- 1 was not significantly greater than zero for colour search in contiguous displays, $t(25) = 1.57$, $p = .128$.

With regard to first fixations of number targets, the main effect of step, $F(2,50) = 124.74$, $p < .001$, $\eta^2_G = .46$, was significant, but the effects of target, $F(1,25) = .89$, $p = .353$, and displays configuration were not, $F(1,25) = .09$, $p = .768$. The two-way interaction between target and step was significant, $F(2,50) = 5.56$, $p = .008$, $\eta^2_G = .04$, as was the three-way interaction, $F(2,50) = 7.68$, $p = .001$, $\eta^2_G = .07$. No other interactions were significant, $F <= 2.05$, $p >= .101$. Post-hoc comparisons revealed that when monitoring for both target types relative to only numbers, a greater proportion of number targets was first fixated at T, $t(25) = 3.33$ $p = .003$. In contiguous displays, when monitoring for both target types relative to only numbers, there was no difference in the proportion of number targets first fixated at T+/-1, $t(25) = 1.83$, $p = .079$, or T+/-2, $t(25) = 0.36$, $p = .722$. However, in discrete displays, when monitoring for both target types relative to only numbers, a smaller proportion of number targets was first fixated at T+/-1, $t(25) = 2.46$, $p = .021$, and T+/-2, $t(25) = 3.30$, $p = .003$. Analysis of fixations and refixations to number targets and TPDs showed a mean of 1.22 ($SD = 0.16$) fixations were made to targets, and 4.57 ($SD = 1.34$) and 1.97 ($SD = 0.25$) total fixations to TPDs one and two steps from the target number respectively. Background distractors at each of the remaining three steps from the target number received an average of 4.88 ($SD = 1.25$) fixations.

With the same approach as for colour targets, the effect of predicting forthcoming number targets was explored with respect to RT and false alarm rate for targets first fixated at T compared to those first fixated as TPDs at T +/- 1 (these data are also shown in Figure 4.5). There was no significant difference in RT between number targets first fixated as TPDs at T +/- 1 and those first fixated at T for: (1) number search in contiguous displays, $t(20) = .44$, $p = .663$; (2) number search in discrete displays, $t(18) = 1.53$, $p = .143$; (3) dual-target search in contiguous displays, $t(21) = 1.49$, $p = .152$; and (4) dual-target search in discrete displays, $t(19) = .33$, $p = .747$. The false alarm rate for number stimuli first fixated as TPDs at T +/- 1 was significantly greater than zero for: (1) number search in contiguous displays, $t(25) = 3.00$, $p = .006$; (2) number search in discrete displays, $t(25) = 2.37$, $p = .026$; (3) dual-target search in contiguous displays, $t(24) = 2.79$, $p = .010$; and (4) dual-target search in discrete displays, $t(25) = 2.94$, $p = .007$.

Together, these data suggest that the ability to detect either category of target predictively was reduced by the need to monitor concurrently for the second category of target. There was an effect of display type on predictive detection, but this was limited to number targets. With respect to number stimuli, in number only search, there was greater evidence of predictive detection in discrete displays than contiguous. Refixation of TPDs one step from the target occurred at a similarly high rate for both colour and number stimuli, indicative of a high rate of re-checking of these stimuli. The refixation rate of number stimuli in background states was high, likely due to the small size of the number set. Predictive detection was not associated with faster responses and fixating target predictive stimuli was associated with false alarms.

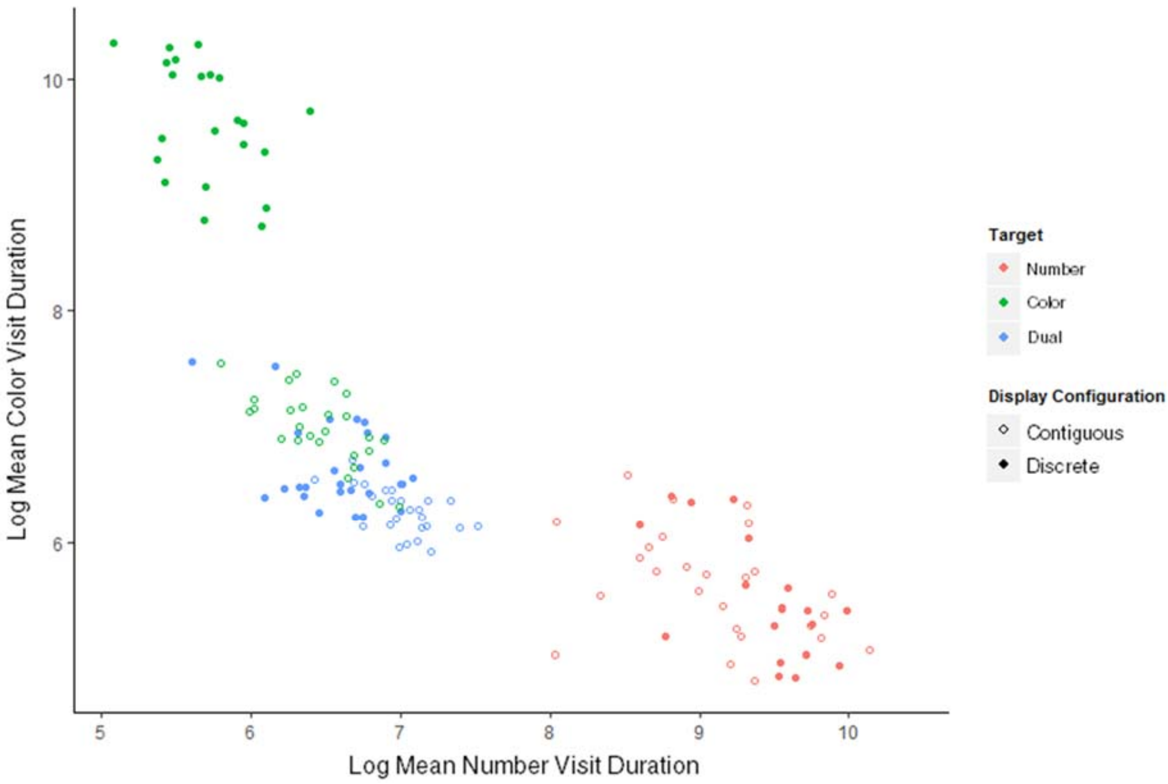

Figure 4.3. Log mean visit durations to colour (y-axis) and number (x-axis) stimulus arrays in all conditions.

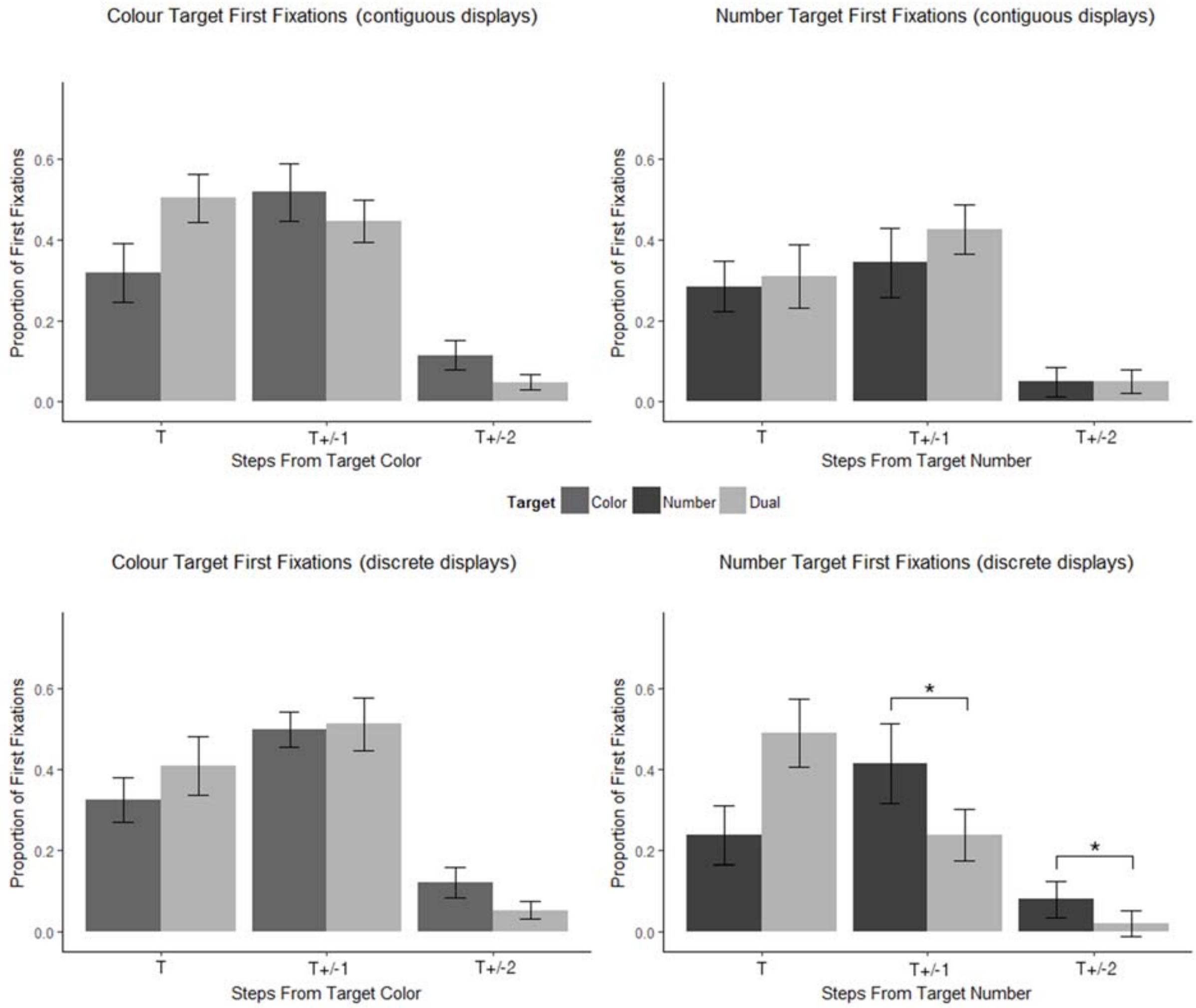

Figure 4.4. Proportion of first fixations to targets, TPDs +/- 1 step from a target state and TPDs +/- 2 steps from a target state in all search and display configurations (error bars show 95% CIs and '*' indicates a pairwise comparison where p < .05; additional significant pairwise comparisons are not shown but are reported in the text).

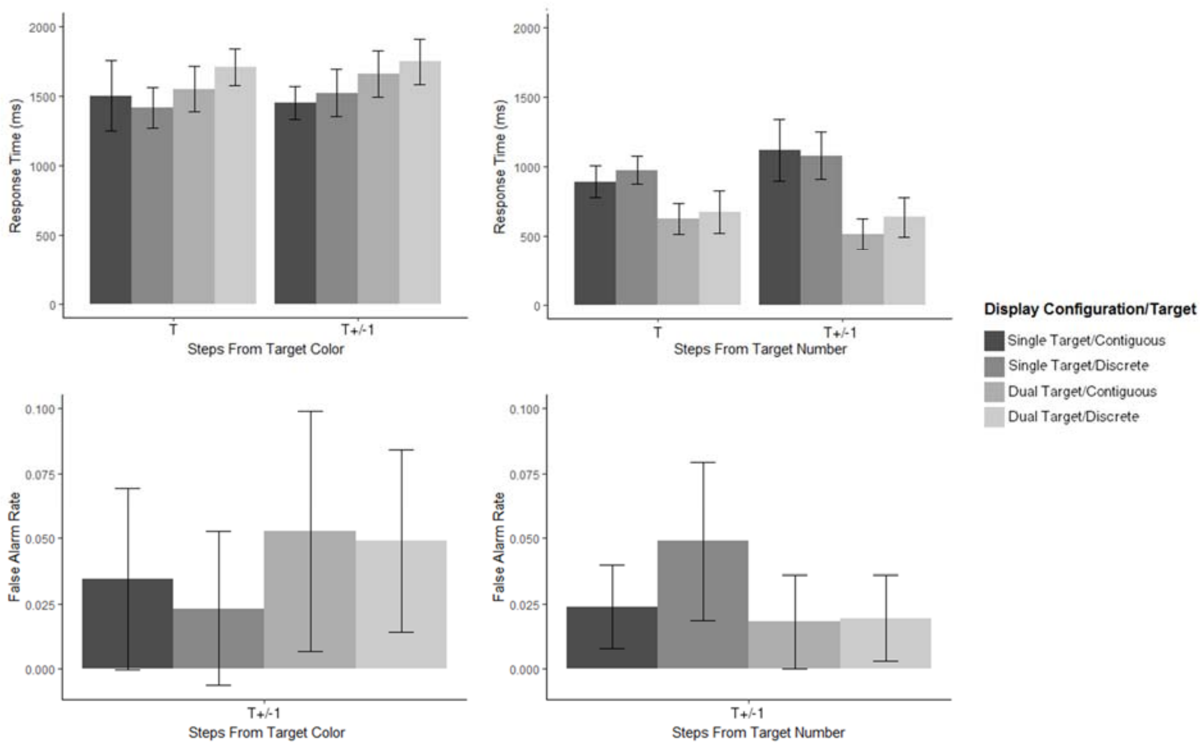

Figure 4.5. Response time (RT) for forthcoming colour and number targets first fixated at T and as TPDs at T+/-1 step (top) and false alarm rate for TPDs first fixated at T+/-1 (bottom; error bars show 95% CIs).

4.4 Discussion

The present study examined how the ability to predictively monitor and detect targets within dynamically changing displays was influenced by the need to monitor for two target categories. It was hypothesized that target detection and predicting monitoring would be worse when searching for targets in two categories compared to one. The behavioural results showed that while targets were accurately detected in both single and dual-target conditions, RTs were faster when monitoring for a single target of either type compared to both. This confirmed that monitoring simultaneously for both colour and number targets slowed detection relative to when monitoring for either target category alone. This is consistent with previous results found in dual-target visual search studies (e.g., Menneer et al., 2004). The eye movement data show longer fixation durations when monitoring for both targets than either target individually. Furthermore, in all conditions other than when monitoring for numbers in contiguous displays, there was evidence of reduced predictive fixations to both colour and number targets. This evidence came from an increase in first fixations made to targets after onset and a decrease in first fixations to TPDs one (in the case of numbers in discrete displays) or two steps (in the case of colour displays) from becoming targets. Together, these data show that searching for targets across two categories involves an increase in the time required for making decisions and a reduction in the ability to monitor predictively for target onsets.

Display configuration did influence the mean visit duration to both colour and number sets. In both single-target searches, colour and number, contiguous displays led to longer visits to the irrelevant stimulus set relative to discrete displays. In dual-target search, visits to the number set were longer in contiguous displays and visits to the colour set were longer in discrete displays. In dual-target search, display configuration had no effect across behavioural and first fixation eye movement measures in relation to monitoring for colour targets. In contrast, display configuration did influence the likelihood of predictive fixations to target predictive number items in dual-target conditions. It is suggested that these data indicate that participants prioritized monitoring for colour targets despite receiving no instruction to do so. This remained qualitatively unchanged between conditions and was consistent between participants. In contrast, monitoring for number targets received lower priority and was aided when the number set was presented contiguously but disadvantaged when presented discretely.

Together with results from Chapters 2 and 3, these findings demonstrate five important facts about monitoring for targets in dynamically changing displays: (1) when searching for a single target, predictive monitoring and detection is possible not only for colour targets, but also for number targets and, in the latter case, is supported by an ordered numerical scale; (2) the cost to searching for two categories of target is mirrored in a cost to search guidance that reduces the ability to monitor predictively for targets; (3) in dual-target searches, display configuration only influences the monitoring of targets that are not prioritized; (4) predictive monitoring can be carried out in the same way for a range of different stimulus set sizes, including 4, 20 and 108; (5) predictive monitoring is characterized by false alarms resulting from premature responses to forthcoming targets, although the present results do not suggest that predictive monitoring is an inferior strategy.

Why does the need to monitor for multiple categories of target reduce the ability to engage in predictive monitoring? One possibility is that predictive monitoring relies on specifying a broad template that includes a range of colours (or numbers) and identifies items that might be targets. Once potential targets are identified, a second, more specific, template is used to evaluate target identity. It is suggested that coordinating the use of both broad and specific templates is not possible when monitoring for two categories of target. In support of this explanation is a body of evidence on the costs to attentional guidance when having to search for more than one colour target simultaneously (Godwin, Menneer, Cave, & Donnelly, 2010; Menneer et al., 2008; Stroud et al., 2012, 2011).

It is important to note that the dual-target condition in the present study presents a greater challenge than these comparatively simple search tasks from the previous literature. In one respect, the heterogenous dynamic changes of stimuli in the present task produce an environment where detecting a target onset may be more difficult (von Mühlenen et al., 2005). A more important consideration is that the dual-target condition in present task involves maintaining and switching between two complex task sets. These sets include both broad and specific target templates, as well as appropriate stimulus-response mappings. The general costs associated with switching between task sets are well established (e.g. Monsell, 2003; Pashler, 2000), but a specific problem in the present case likely arises from limitations in the capacity to store or access broad and specific colour and number target templates via working memory (WM).

While the specific role of WM in relation to target templates in visual search is not certain (Boettcher et al., 2013; Drew et al., 2016) there is a wide body of evidence for the involvement of WM in the storage of, or at least access to, target templates (for a review see Olivers, Peters, Houtkamp & Roelfsema, 2011). In the present task, monitoring for colour and number target onsets must rely on storing or accessing two sets of target representations via WM and alternating between them. Using WM to coordinate a complex set of colour and number templates may impact monitoring by reducing the available working memory capacity (WMC) available for broad range templates that might facilitate predictive fixations to targets.

In conclusion, the present study provides a first insight into how predictive monitoring is managed in the case of search for two target categories. These findings have implications, across a range of applied domains, for the design of electronic visual displays that integrate multiple categories of information. If a secondary source of information can be closely integrated with a primary source, in a way that minimizes attentional shifts, then this may facilitate the prediction of target information. In the example of marine radar, this might involve the integration or overlaying of alphanumeric indicators of position, direction and speed within a central map, rather than positioning these values peripherally within discrete regions. Furthermore, with recent advances in the availability and popularity of augmented and virtual reality devices, this is not just a problem faced by those in highly specific applied scenarios, but by user interface designers more broadly. In taking advantage of the flexibility offered by modern computing and display technology, it is important for developers and designers to determine the optimal way to integrate different sources of complex visual information. Regardless of the specific application, it is difficult to imagine a case where facilitating effective attentional guidance would not be desirable.

Chapter 5

General Discussion

5.1 Motivation for Thesis

The present section serves to recount the motivation for thesis, both as a whole and in terms of the individual chapters. In doing this, it is important to remember that visual search is an everyday phenomenon, but it also has a role in a number of critically important scenarios. We complete many daily tasks without even considering the visual searches they involve, for example, finding keys in a bag or locating the correct change for a vending machine. However, in addition to these day-to-day activities, it is also part of many critically important applied scenarios, often referenced in the literature, such as X-ray baggage imaging and cancer screening (Godwin, Menneer, Cave, Helman, et al., 2010; Horowitz, 2017). This range of applications of visual search, from the commonplace to the critical, is precisely why it remains an important and interesting area of study.

Research in this area has often been undertaken by those seeking a clear set of practical implications within a given context, for example, militaries hoping to improve vigilance in radar operators and transport authorities wishing to stop improvised explosive devices being smuggled onto aircraft. Studies have addressed applied questions surrounding such problems, both in controlled laboratory settings and with experiments in real-world situations. Fortunately, theoretical advances have accompanied and informed practical gains and implications. Important examples of specific areas of study within the visual search literature that have been driven forward by practical considerations, but yielded important theoretical advances, are target prevalence effects, dual-target costs and satisfaction of search effects. Chapter 1 reviewed literature relating to all three of these effects. All have a clear basis in real-world problems, but their study has also informed significant theoretical advances relating to attentional guidance, perceptual sensitivity and response bias.

Applied problems have had an important role in motivating studies of visual search and this continues to hold true with the emergence of new practical visual problems. Looking back over the study of visual search, tasks have typically involved fixed location and unchanging sets of stimuli that are presented for a short time in a series of discrete trials. Participants are normally told to search for a particular target item and must make a binary ‘absent’ or ‘present’ response to each trial. Such tasks provide an effective and controlled basis for the study of many visual search phenomena, and have provided significant insights into the mechanisms behind, for example, prevalence, dual-target and satisfaction of search effects. However, the increasing integration of electronic displays and dynamic data visualizations in a variety of domains means that individuals frequently conduct searches in environments that are not static and require monitoring over an extended period of time. These features are representative of a set of task demands that will become more common and, importantly, are distinct from those of traditional static search tasks. In a traditional search task, any stimulus presented on screen has a single identity for the duration of a trial. In comparison, a stimulus presented on an electronic heatmap might switch between multiple colour identities over an extended period of time. What parameters influence target detection in such a task? In what way do these differences influence the applicability of well-established search effects to this type of task? If stimuli change over time, can target onsets be predicted? These questions stem from just a single example, but understanding how search processes operate in the context of dynamically changing stimuli presented for extended durations, and how a variety of existing, well-established, visual search effects are influenced by the demands of such a task, is an important and under-studied problem.

In seeking to better understand this kind of visual search, studying performance based on data aggregated across large groups is useful, but it is also important to consider what factors might account for variance in performance at the level of the individual. Identifying individual factors that can predict performance and determining a set of individual characteristics associated with good performance is desirable for a number of reasons. In applied situations where the cost of an error is high, such an understanding would allow the selection of individuals who can complete a task with a low error rate. In addition, studying the impact of prevalence and dual-target search with such an approach may reveal individual traits that heighten such effects. Understanding what individual characteristics predict effects like these may help to explain why these effects occur and how costs might be mitigated. If particular individual characteristics are malleable and can be improved by specific training, then this may provide a means of facilitating or accelerating overall training and boosting practice benefits.

In selecting individual factors for study, one should be guided, in part, by real-world considerations. Individuals conducting visual searches and monitoring in real-world tasks may be subject to high levels of anxiety and situational stress, especially if the costs of making errors is high. Anxiety has a well-established impact upon attentional control and appeared to be a likely candidate for a predictor of variance in target detection (Eysenck et al., 2007; Richards et al., 2014). Intolerance of uncertainty is a related construct that reflects the extent to which an individual experiences and deals with worry regarding uncertain future events. While this may lack importance when considering performance in static search tasks, in dynamic tasks, when stimuli can change over time and there is inevitably some uncertainty regarding their future states, such a characteristic has direct theoretical relevance. A further characteristic, of general importance across a range of visuo-cognitive tasks and a specific moderating relationship with anxiety, is working memory capacity. Working memory capacity has also been shown to predict performance on a range of search tasks, particularly those requiring greater top-down control (Kane et al., 2006; Peltier & Becker, 2016, 2017). Individuals with greater working memory capacity have also been shown to be less influenced by attentional biases associated with anxiety and it has been suggested that working memory capacity can have a compensatory effect in this regard. Importantly, working memory capacity is malleable and has the potential to be improved with appropriate training (Jaeggi et al., 2008; Klingberg, 2010), potentially translating into benefits for target detection and monitoring.

Two potential means of achieving improvements in working memory function are working memory training and transcranial direct current stimulation of the dorsolateral prefrontal cortex. Working memory training involves repeated regular sessions of a computerized working memory task that adapts to individual performance. Previous studies have found that the benefits of such training can transfer to both untrained working memory tasks and more general measures of fluid intelligence. Transcranial direct current stimulation involves a short period of cortical stimulation via electrodes placed on the scalp. Targeting stimulation on a region like the dorsolateral prefrontal cortex has been shown to provide benefits to working memory and attentional control. These interventions have distinct mechanisms of action, but both involve a procedure that could be integrated into training routines in order to benefit target detection and monitoring performance when engaged with dynamic visual displays.

The present thesis introduces a new dynamic visual search paradigm to address the issues outlined above. Chapter 1 provides a broad review of the literature on visual search, including particular consideration of effects relating to target prevalence and dual-target search, in order to provide context for the novel dynamic search task developed as part of this work. It also considered some of the ways in which state and trait anxiety, intolerance of uncertainty, and verbal and spatial working memory capacity might predict search behaviour, target detection and monitoring. The review considered some of the specific ways in which the two techniques mentioned above, working memory training and transcranial direct current stimulation, could influence these factors and potentially translate into improvements in target detection and monitoring. The subsequent chapters detail a series of experiments that address four specific questions relating to a number of themes identified in Chapter 1:

1. How does the visual search of dynamically changing displays differ from standard visual search, and can contingencies expressed in display changes allow the prediction of target onsets?
2. To what extent do individual differences in state and trait anxiety, intolerance of uncertainty, verbal and spatial working memory capacity, and interactions between these factors, predict target detection and monitoring performance?
3. Can target detection and monitoring performance be improved through interventions that target working memory mechanisms, i.e., n-back training and prefrontal transcranial direct current stimulation?
4. How are the mechanisms of target detection and monitoring in dynamic displays influenced by variation in specific task features and parameters? Do they function similarly across different categories of stimulus and display configurations, and how are they affected by target prevalence and the need to search for multiple targets simultaneously?

5.2 Key Findings

5.2.1 Forthcoming Targets can be Predicted and Likely Target Locations are Monitored

Chapter 2 introduced the novel dynamic visual search task that would go on to form the basis of all of the experiments presented in this thesis. The task was designed to address the broad question of how dynamically changing displays are searched and monitored, and, more specifically, whether target onsets could be predicted from display changes. Chapter 2 provided initial evidence that likely target locations could indeed be predicted from the changing states of distractors, but that this was only possible when stimuli changed according to single steps on a psychologically ordered colour scale. This finding was supported by evidence that showed, in conditions of ordered change, forthcoming targets were first fixated as target predictive distractors and then monitored via additional fixations. This finding was repeated across six experiments in Chapters 2, 3 and 4. It is suggested that this predictive detection is supported by guidance from a broad attentional range template centred about the target and a subsequent decision involving a more precise target template.

This type of predictive detection was a robust finding and was not just restricted to the detection of colour stimuli. Chapter 4 provides evidence that numerical stimuli, changing according to single steps on a semantically ordered scale, were detected in the same way. Together, Chapters 2 and 3 provide evidence that predictive detection is possible: (1) over a wide range of target prevalence levels, from very low to high; (2) a range of stimulus set sizes, from 4 numbers to 108 coloured squares; and (3) in different spatial configurations with varied levels of visual clutter. Chapter 4 also provided evidence that the ability to engage in predictive detection was reduced by the need to monitor for two categories of target simultaneously. It is also important to note that predictive detection was not always associated with improvements to the speed or accuracy of the detection of target onsets. In Chapter 2, predictive detection was, in some cases, associated with less accurate target detection. However, in the higher target prevalence conditions in the experiments in Chapter 3, predictive detection did speed response time.

5.2.2 Search Performance is Predicted by Intolerance of Uncertainty and Verbal Working Memory Capacity

Although the nature of the relationship between intolerance of uncertainty changed with the altered task parameters between the experiments in Chapters 2 and 3, it was repeatedly linked with behavioural performance. In Chapter 2, intolerance of uncertainty was found to positively predict false alarm rate. In the comparatively low target prevalence conditions of Experiment 3 in Chapter 2, individuals with higher intolerance of uncertainty were less able to avoid making incorrect responses to target-similar items. This result was consistent with intolerance of uncertainty being associated with a shift in response criterion, biasing some individuals towards making a ‘target present’ response. A different, but theoretically consistent, result was observed in the higher prevalence conditions of the experiments in Chapter 3: intolerance of uncertainty was positively associated with hit rate. If individuals with higher intolerance of uncertainty are more likely to make ‘target present’ responses, it stands to reason that they should perform better in situations where this has a greater probability of being the correct response.

A further repeated finding, across Chapters 2 and 3, was the interaction between intolerance of uncertainty and verbal working memory capacity. In Chapter 2, verbal working memory capacity was found to moderate the effect of intolerance of uncertainty upon false alarm rate, such that the false alarm rate of individuals with higher verbal working memory capacity was not strongly associated with intolerance of uncertainty. Parallels exist between this interaction and the compensatory effects of high working memory capacity for anxious individuals predicted by Attentional Control Theory. Verbal working memory capacity was also found to interact with the effect of intolerance of uncertainty upon hit rate that was observed in Chapter 3. In this interaction, higher verbal working memory capacity was again associated with better performance, but, in this case, when allied with higher intolerance of uncertainty. Together, the change of behavioural outcome (from false alarm rate to hit rate) and the direction of this interaction may seem curious. They are, however, consistent with an account where IU influences response criterion and verbal WMC influences perceptual sensitivity. In both sets of results, greater IU appeared to be associated with a lower response criterion, with responses being made more readily. When target prevalence was low, in Chapter 2, this was evident in terms of an increased false alarm rate. When target prevalence was high, in Chapter 3, this was evident in terms of an increased hit rate. In both cases, high verbal WMC beneficially moderated the effects of IU, reducing false alarm rates and increasing hit rates for individuals with high IU. These results suggest that verbal WMC supports perceptual sensitivity, with individuals with higher verbal WMC being better able to discriminate between targets and distractors. The lack of a reliable effect of spatial working memory capacity on behavioural outcomes across Chapters 2 and 3 was unexpected. However, these chapters provide important evidence of the role verbal working memory in a complex monitoring task where stimuli can have a range of closely spaced identities.

5.2.3 Working Memory Training and Transcranial Direct Current Stimulation did not Influence Search Performance

Guided by findings from Chapter 2, where verbal working memory capacity moderated the effect of intolerance of uncertainty on false alarm rate, Chapter 3 set out to target and improve working memory capacity with a view to translating any benefits to improved task performance for those with high intolerance of uncertainty. Chapter 3 introduced two interventions with distinct approaches to achieving this aim.

One of these approaches was a program of adaptive dual n-back working memory training, which aimed to improve working memory capacity following a series of 15 daily sessions of computerized training. The literature on memory training has, over recent years, swollen with a great number of contentious articles and published dialogues arguing that working memory training does or does not offer broad benefits that transfer to untrained tasks. The review of this literature in Chapter 1 discussed evidence from a number of studies and reviews that indicated working memory training had the potential to benefit performance in untrained tasks. However, no evidence was found of benefits that transferred to the search task, or indeed, simple verbal and spatial working memory capacity tasks. The only improvement associated with the working memory training was observed in the training task itself. The most likely explanation for these results is a lack of power, as previously observed transferrable training benefits have sometimes involved relatively small effects. Training adherence is also a significant issue and, while participant performance was monitored, the variation in individual engagement and training environment may have influenced the results.

The second approach involved transcranial direct current stimulation of the dorsolateral prefrontal cortex. The literature reviewed in Chapter 1 revealed a range of stimulation montages and electrode placements in studies examining effects on working memory and attentional control. The work in Chapter 3, however, revealed no reliable benefits of stimulation to performance in the search task and no benefits in simpler tests of verbal and spatial working memory and attentional control. The effects of transcranial direct current stimulation are known to be short-lived and there is inevitably a reduced likelihood of observing effects over time. The procedure used in Chapter 3, with multiple tasks over the course of an experimental session, focused on the main aim of this work and prioritized the search task by including it at the beginning of the session. Unfortunately, this does make it difficult to determine whether effects in the later tasks may have been observed if they had been included at an earlier stage in the procedure.

Despite the null results for these interventions, Chapter 3 provided additional evidence of the role of intolerance of uncertainty, together with the moderating influence of verbal working memory capacity, in predicting behavioural performance on this complex search and monitoring task. This additional evidence, from conditions of higher target prevalence, supported the reliability of the previous findings discussed above. The experiments presented in Chapters 2 and 3 combine to highlight an important role of working memory capacity, at least for a subset of individuals with high intolerance of uncertainty. These findings, together with the null effects of the interventions in Chapter 3 in terms of search task performance and the two specific working memory capacity tasks, suggest that the most likely explanation is that neither working memory training nor transcranial direct current stimulation (following the present set of stimulation parameters) were able to improve working memory capacity.

5.2.4 Target Prevalence and Dual-target Search Influence Target Detection and Predictive Monitoring

The results across Chapters 2, 3 and 4 establish that target prevalence and dual-target search have similar effects to those observed in static searches. In Chapter 2, low target prevalence resulted in a higher false alarm rate compared to high prevalence. Comparing results between the experiments in Chapters 2 and 3 further revealed increased hit rates and decreased response times and false alarm rates in the higher prevalence conditions of the experiments in Chapter 3 relative to the lower prevalence levels of the final experiment in Chapter 2. Chapter 4 examined a specific type of dual-target search, where participants searched for colour and numerical targets and up to one target of either type could be present simultaneoulsy. A significant dual-target cost to response time was found, such that it was longer when searching for two target categories compared to one. All of these results are consistent with well-established behavioural results from static search tasks and serve to further establish that these effects hold true when searching dynamic displays too.

The dynamic nature of the present task provides a further context for the consideration of such effects. In dynamic visual search tasks of this type, the effects of prevalence and dual-target search should not only be considered in terms of basic behavioural measures of hit rate and response time, or indeed simple eye movement measures, but also specifically in terms of the impact on predictive detection and monitoring over time. Together, the results from Chapters 2 and 3 indicate that higher target prevalence allowed for greater target prediction and facilitated a benefit of prediction to response time. In addition to slower response times to both numerical and colour stimuli, there was also evidence of a dual-target cost to target prediction in Chapter 4. While the cost to response times slowed responses to both sets of stimuli similarly, there was an asymmetry in the cost to target prediction, with the predictive detection of numerical stimuli suffering a greater cost than that of colour stimuli. This cost also had a specific dependency upon display configuration, only being evident in displays that spatially segregated the two stimulus sets. These findings go some way to establishing when and to what extent some well-established visual search effects translate to the search and monitoring of a dynamic environment.

5.3 Implications and Future Work

5.3.1 Guiding the Interpretation of Existing Visual Search Theory in the Context of Dynamic Tasks

A certain class of task has dominated the study of visual search, involving sets of discrete items, with fixed identities, presented for short durations and requiring a binary response of 'target present' or 'target absent'. These tasks have yielded important findings about the mechanisms that underlie visual search and their limitations. The present thesis highlights limitations in what can be learned from such paradigms and provides evidence that new dynamic paradigms, like that which formed the basis of the experiments presented here, are required to better understand visual search in a wider range of scenarios that reflect many real-world situations.

One way to improve our understanding of visual search is to examine the extent to which search theory is applicable within a dynamic search paradigm and to consider new metrics by which performance and eye movements can be analysed. The present thesis takes this approach in the exploration of target prevalence and dual-target effects, and in the use of a novel eye movement measure of target prediction, however, it is far from exhaustive in this respect. In seeking to explain the findings of the present thesis, over the course of Chapters 2, 3 and 4, an account is proposed that: (1) explains predictive target detection in terms of the combined application of broad and precise attentional templates; and (2) describes the effects of intolerance of uncertainty on target detection across varying target prevalence levels in terms of shifts in response criterion and perceptual sensitivity. Further study is required to determine how, within the bounds of such an account, these templates guide search and function together, and how these individual factors interact to produce these behavioural effects.

The majority of the experimental work in the present thesis concentrates on the detection of colour targets. Chapter 4 goes some way to extending the findings of Chapters 2 and 3 to an alternative numerical stimulus set. The experimental work in Chapter 4 was, however, focused on the behavioural and eye movement effects of the specific dual-target manipulation, and this chapter does not consider the same measures of individual differences as Chapters 2 and 3. Chapter 4, therefore, lays the groundwork not only for further examination of search and monitoring in displays involving multiple stimulus types, but also for specific consideration of how the influence of individual differences in intolerance of uncertainty and working memory capacity might transfer to a range of different dynamic search environments.

5.3.2 Informing the Design of Visual Displays and the Selection of Personnel in Applied Scenarios

In addition to its implications for visual search as a field of study, the present thesis also has significant practical implications for the design of electronic visual displays and the selection of personnel across a range of real-world scenarios. The first of these is for the design of scales used to represent changing information in electronic visual displays. Chapter 2 presents evidence that when elements within displays change according to a colour scale that ensures discontinuity and highly salient colour changes, target detection performance suffered. Furthermore, while Chapter 4 does not directly address this same question, the similarities between the colour and number search tasks within this chapter suggest that the same could be true of numerical scales. Even if this result only applies to colour scales, there is the clear implication for those designing such scales, that they should be both psychologically ordered and involve only small incremental changes. Future work should further explore the extent to which the findings of Chapters 2 and 3 generalize to other stimulus types.

An additional design implication arises from the dual-target results presented in Chapter 4. When searching for targets from two categories, a display configuration which spatially separated the two stimulus sets reduced the ability to predictively monitor for one category of target. While task specific factors may have a greater influence in any given case than the effects responsible for these results, the potential implications cannot be ignored. The foremost of these is that when designing a visual display for a task which involves seeking target information that fits into multiple categories, in order to maximize the ability to predict forthcoming targets, displays should spatially integrate both sources of information.

The repeated findings across Chapters 2 and 3, linking intolerance of uncertainty and verbal working memory capacity to target detection performance, have significant implications for the selection of personnel in real-world monitoring tasks. It is particularly important to have reliable selection tests in safety critical domains like x-ray baggage screening, not only in terms of outcomes while on the job, but also receptiveness to training (Schwaninger, Hardmeier, & Hofer, 2004; Schwaninger, 2016). Selecting individuals with a lower probability of missing targets, or mistaking non-targets for targets, would be highly desirable in this and other real-world scenarios where the cost of making an error is high. Identifying further characteristics that might also predict performance, or interact with the characteristics identified in the present thesis, could prove a fruitful avenue of further study. Given the extended durations and uncertain outcomes of dynamic search and monitoring tasks, characteristics, like intolerance of uncertainty, that relate to how individuals deal with task outcomes might be particularly important. One such character dimension is the extent to which someone is a satisficer or a maximizer, satisficers being more likely to settle for a ‘good enough’ outcome and maximizers always wishing to achieve the best possible outcome (Schwartz et al., 2002). Other individual factors may have a useful role, not in the selection of personnel, but monitoring their development and performance over time. For example, a recent study has demonstrated a mediating effect of work-family conflict upon the impact of workload on job satisfaction and emotional exhaustion (Baeriswyl, Krause, & Schwaninger, 2016).

5.3.3 Emphasizing the Importance of an Approach that Acknowledges Individual Differences

The present thesis provides further evidence that high-level individual differences cannot be ignored in the study of complex visual tasks. Individual variation in cognitive capacities and personality traits is clearly a significant source of variance in performance in this kind of task and an awareness of this must be incorporated into the study of the mechanisms underlying performance in novel tasks and paradigms. Future studies should make use of pre-screening and designs that examine stratified samples with maximal differences. Such an approach will facilitate the assessment of effect sizes related to specific individual characteristics. It will also be particularly beneficial in determining the applied significance of any such work, and how different personality traits and cognitive functions interact. The present thesis identified a set of characteristics that were predictive of search performance and this understanding informed the interventions employed in Chapter 3. While these attempts to improve search and monitoring performance were unsuccessful, greater knowledge of other relevant individual characteristics, and how they influence performance on this type of task, may reveal additional routes via which potentially performance enhancing interventions might influence search.

5.4 Concluding Remarks

Humans are frequently required to conduct visual searches for target information contained within complex, dynamically changing, electronic visual displays. The introduction of such displays into a wide range of real-world scenarios is relatively recent when viewed against the history of visuo-cognitive psychology. The study of this type of visual search has lagged behind the technological advancements that have allowed electronic displays to permeate both our daily lives and many specific, and highly important, applied tasks in a variety of domains. This thesis attempts to address the lack of prior research in this area with the introduction of a novel dynamic search and monitoring task and an approach that considers individual variation in a number of theoretically relevant cognitive and personality traits.

Chapter 2 introduces this novel task, establishes the limits of predictive monitoring, identifies intolerance of uncertainty and its interaction with verbal working memory capacity as predictors of false alarm rate, and examines the prevalence effect in the context of this new task. Chapter 3 revisits the same task with modified prevalence parameters and examines two interventions, working memory training and transcranial direct current stimulation, with the aim of improving behavioural performance. While Chapter 3 did not yield any such improvements, it provided further evidence of the role of intolerance of uncertainty and its interaction with verbal working memory capacity in predicting hit rate in conditions of higher target prevalence. Chapter 4 extended some of the findings regarding the nature of predictive monitoring from Chapters 2 and 3 to a distinct numerical scale and showed that it is not only dynamically changing colour stimuli that are monitored in this way. In conclusion, the present thesis establishes important differences between the visual search of static and dynamically changing displays, identifies key individual predictors of performance and has critical applied implications for real-world search and monitoring tasks.

Appendices

Appendix A: Chapter 2 Search Task Video

This video shows a 40 second trial of the search task used in Experiments 1, 2 and 3 in Chapter 2. It shows eye and mouse cursor movements that were generated by the experimenter. The video is available at https://goo.gl/8vYBW6 and on the disc affixed to the rear cover of this document.

References

Anderson, E. J., Mannan, S., Rees, G., Sumner, P., & Kennard, C. (2008). A role for spatial and nonspatial working memory processes in visual search. *Experimental Psychology*, *55*(5), 301–312. http://doi.org/10.1027/1618-3169.55.5.301

André, S., Heinrich, S., Kayser, F., Menzler, K., Kesselring, J., Khader, P. H., … Mylius, V. (2016). At-home tDCS of the left dorsolateral prefrontal cortex improves visual short-term memory in mild vascular dementia. *Journal of the Neurological Sciences*, *369*, 185–190. http://doi.org/10.1016/j.jns.2016.07.065

Antal, A., Kincses, T. Z., Nitsche, M. A., & Paulus, W. (2003). Modulation of moving phosphene thresholds by transcranial direct current stimulation of V1 in human. *Neuropsychologia*, *41*(13), 1802–1807. http://doi.org/10.1016/S0028-3932(03)00181-7

Antal, A., Nitsche, M. a, Kruse, W., Kincses, T. Z., Hoffmann, K.-P., & Paulus, W. (2004). Direct current stimulation over V5 enhances visuomotor coordination by improving motion perception in humans. *Journal of Cognitive Neuroscience*, *16*(4), 521–527. http://doi.org/10.1162/089892904323057263

Antal, A., & Paulus, W. (2008). Transcranial direct current stimulation and visual perception. *Perception*, *37*(3), 367–374. http://doi.org/10.1068/p5872

Ariga, A., & Lleras, A. (2011). Brief and rare mental “breaks” keep you focused: deactivation and reactivation of task goals preempt vigilance decrements. *Cognition*, *118*(3), 439–443. http://doi.org/10.1016/j.cognition.2010.12.007

Attar, N., Schneps, M. H., & Pomplun, M. (2016). Working memory load predicts visual search efficiency: Evidence from a novel pupillary response paradigm. *Memory &*

Cognition, 1–12. http://doi.org/10.3758/S13421-016-0617-8

Au, J., Buschkuehl, M., Duncan, G. J., & Jaeggi, S. M. (2016). There is no convincing evidence that working memory training is NOT effective: A reply to Melby-Lervåg and Hulme (2015). *Psychonomic Bulletin & Review*, *23*(1), 331-337. http://doi.org/10.3758/s13423-015-0967-4

Au, J., Katz, B., Buschkuehl, M., Bunarjo, K., Senger, T., Zabel, C., Jaeggi, S. M., & Jonides, J. (2016). Enhancing Working Memory Training with Transcranial Direct Current Stimulation. *Journal of Cognitive Neuroscience*, *28*(9), 1419–1432. http://doi.org/doi:10.1162/jocn_a_00979

Au, J., Sheehan, E., Tsai, N., Duncan, G. J., Buschkuehl, M., & Jaeggi, S. M. (2014). Improving fluid intelligence with training on working memory: a meta-analysis. *Psychonomic Bulletin & Review*, *22*(2), 366–377. http://doi.org/10.3758/s13423-014-0699-x

Bach, M. (1996). The Freiburg Visual Acuity test--automatic measurement of visual acuity. *Optometry and Vision Science*, *73*(1), 49–53.

Baeriswyl, S., Krause, A., & Schwaninger, A. (2016). Emotional exhaustion and job satisfaction in airport security officers - work-family conflict as mediator in the job demands-resources model. *Frontiers in Psychology*, 7, 1–13. http://doi.org/10.3389/fpsyg.2016.00663

Barrett, D. J. K., & Zobay, O. (2014). Attentional control via parallel target-templates in dual-target search. *PLoS ONE*, *9*(1). http://doi.org/10.1371/journal.pone.0086848

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2014). Fitting Linear Mixed-Effects Models using lme4. *Journal of Statistical Software*, *67*(1), 51.

http://doi.org/10.18637/jss.v067.i01

Becic, E., Kramer, A. F., & Boot, W. R. (2007). Age-related differences in visual search in dynamic displays. *Psychology and Aging*, *22*(1), 67–74. http://doi.org/10.1037/0882-7974.22.1.67

Beck, V. M., Hollingworth, a., & Luck, S. J. (2012). Simultaneous Control of Attention by Multiple Working Memory Representations. *Psychological Science*, *23*(8), 887–898. http://doi.org/10.1177/0956797612439068

Bellenkes, A. H., Wickens, C. D., & Kramer, A. F. (1997). Visual scanning and pilot expertise: The role of attentional flexibility and mental model development. *Aviation, Space, and Environmental Medicine*. US: Aerospace Medical Association.

Berbaum, K. S., Franklin, E. A., Jr., Caldwell, R. T., & Schartz, K. M. (2010). Satisfaction of Search in Traditional Radiographic Imaging. *Radiology*, *261*(3), 1000-1001. http://doi.org/10.1148/radiol.11110987

Berggren, N., & Derakshan, N. (2013). Attentional control deficits in trait anxiety: why you see them and why you don't. *Biological Psychology*, *92*(3), 440–446. http://doi.org/10.1016/j.biopsycho.2012.03.007

Berryhill, M. E., & Jones, K. T. (2012). tDCS selectively improves working memory in older adults with more education. *Neuroscience Letters*, *521*(2), 148–151. http://doi.org/10.1016/j.neulet.2012.05.074

Biggs, A. T. (2017). Getting satisfied with "satisfaction of search": How to measure errors during multiple-target visual search. *Attention, Perception, & Psychophysics*, *79*(5), 1352-1365. http://doi.org/10.3758/s13414-017-1300-2

Biggs, A. T., Adamo, S. H., Dowd, E. W., & Mitroff, S. R. (2015). Examining perceptual and conceptual set biases in multiple-target visual search. *Attention, Perception, & Psychophysics*, *77*(3), 844–855. http://doi.org/10.3758/s13414-014-0822-0

Birrell, J., Meares, K., Wilkinson, A., & Freeston, M. (2011). Clinical Psychology Review Toward a definition of intolerance of uncertainty : A review of factor analytical studies of the Intolerance of Uncertainty Scale. *Clinical Psychology Review*, *31*(7), 1198–208. http://doi.org/10.1016/j.cpr.2011.07.009

Bishop, S. J. (2009). Trait anxiety and impoverished prefrontal control of attention. *Nature Neuroscience*, *12*(1), 92–8. http://doi.org/10.1038/nn.2242

Bleckley, M. K., Durso, F. T., Crutchfield, J. M., Engle, R. W., & Khanna, M. M. (2003). Individual differences in working memory capacity predict visual attention allocation. *Psychonomic Bulletin & Review*, *10*(4), 884–889. http://doi.org/10.3758/BF03196548

Boettcher, S. E. P., Drew, T., & Wolfe, J. M. (2013). Hybrid Search in Context: How to search for vegetables in the produce section and cereal in the cereal aisle. *Visual Cognition*, *21*(6), 678–682. http://doi.org/10.1038/jid.2014.371

Boggio, P. S., Bermpohl, F., Vergara, A. O., Muniz, A. L. C. R., Nahas, F. H., Leme, P. B., Rigonatti, S. P., & Fregni, F. (2007). Go-no-go task performance improvement after anodal transcranial DC stimulation of the left dorsolateral prefrontal cortex in major depression. *Journal of Affective Disorders*, *101*(1–3), 91–98. http://doi.org/10.1016/j.jad.2006.10.026

Boggio, P. S., Ferrucci, R., Rigonatti, S. P., Covre, P., Nitsche, M. A., Pascual-Leone, A., & Fregni, F. (2006). Effects of transcranial direct current stimulation on working memory in patients with Parkinson's disease. *Journal of the Neurological Sciences*, *249*(1), 31–38. http://doi.org/10.1016/j.jns.2006.05.062

Boot, W. R., Becic, E., & Kramer, A. F. (2009). Stable individual differences in search strategy? The effect of task demands and motivational factors on scanning strategy in visual search. *Journal of Vision*, *9*(3):7, 1-16. http://doi.org/10.1167/9.3.7

Boot, W. R., Kramer, A. F., Becic, E., Wiegmann, D. a, & Kubose, T. (2006). Detecting transient changes in dynamic displays: the more you look, the less you see. *Human Factors*, *48*(4), 759–773. http://doi.org/10.1518/001872006779166424

Booth, R. W., Mackintosh, B., & Sharma, D. (2017). Working memory regulates trait anxiety-related threat processing biases. *Emotion*, *17*(4), 616–627. http://doi.org/10.1037/emo0000264

Borchert, K. (2016). Visual Digit Span [Computer software]. Millisecond Software LLC. Retrieved from http://www.millisecond.com/download/library/DigitSpan/

Borella, E., Carbone, E., Pastore, M., De Beni, R., & Carretti, B. (2017). Working Memory Training for Healthy Older Adults: The Role of Individual Characteristics in Explaining Short- and Long-Term Gains. *Frontiers in Human Neuroscience*, *11*. http://doi.org/10.3389/fnhum.2017.00099

Brehmer, Y., Westerberg, H., & Bäckman, L. (2012). Working-memory training in younger and older adults: training gains, transfer, and maintenance. *Frontiers in Human Neuroscience*, *6*. http://doi.org/10.3389/fnhum.2012.00063

Broadway, J. M., & Engle, R. W. (2011). Individual differences in working memory capacity and temporal discrimination. *PLoS ONE*, *6*(10). http://doi.org/10.1371/journal.pone.0025422

Brunoni, A. R., & Vanderhasselt, M.-A. (2014). Working memory improvement with non-invasive brain stimulation of the dorsolateral prefrontal cortex: a systematic review and meta-analysis. *Brain and Cognition*, *86*, 1–9. http://doi.org/10.1016/j.bandc.2014.01.008

Buhr, K., & Dugas, M. J. (2002). The Intolerance of Uncertainty Scale: psychometric properties of the English version. *Behaviour Research and Therapy*, *40*(8), 931–945. http://doi.org/10.1016/S0005-7967(01)00092-4

Buhr, K., & Dugas, M. J. (2006). Investigating the construct validity of intolerance of uncertainty and its unique relationship with worry. *Journal of Anxiety Disorders*, *20*(2), 222–236. http://doi.org/10.1016/j.janxdis.2004.12.004

Caggiano, D. M., & Parasuraman, R. (2004). The role of memory representation in the vigilance decrement. *Psychonomic Bulletin & Review*, *11*(5), 932–937. http://doi.org/10.3758/BF03196724

Cain, M. S., Adamo, S. H., & Mitroff, S. R. (2013). A Taxonomy of Errors in Multiple-Target Visual Search. *Visual Cognition, 21*(7), 899-921. http://doi.org/10.1080/13506285.2013.843627

Cain, M. S., & Mitroff, S. R. (2013). Memory for found targets interferes with subsequent performance in multiple-target visual search. *Journal of Experimental Psychology. Human Perception and Performance*, *39*(5), 1398–1408. http://doi.org/10.1037/a0030726

Carleton, N. R. (2016). Fear of the unknown: One fear to rule them all? *Journal of Anxiety Disorders*, *41*, 5–21. http://doi.org/10.1016/j.janxdis.2016.03.011

Carleton, N. R., Duranceau, S., Shulman, E. P., Zerff, M., Gonzales, J., & Mishra, S. (2016). Self-reported intolerance of uncertainty and behavioural decisions. *Journal of Behavior Therapy and Experimental Psychiatry*, *51*, 58–65.

http://doi.org/10.1016/j.jbtep.2015.12.004

Carleton, N. R., Norton, M. A. P. J., & Asmundson, G. J. G. (2007). Fearing the unknown: a short version of the Intolerance of Uncertainty Scale. *Journal of Anxiety Disorders*, *21*(1), 105–117. http://doi.org/10.1016/j.janxdis.2006.03.014

Carlisle, N. B., Arita, J. T., Pardo, D., & Woodman, G. F. (2011). Attentional templates in visual working memory. *The Journal of Neuroscience*, *31*(25), 9315–9322. http://doi.org/10.1523/JNEUROSCI.1097-11.2011

Chun, M. M., & Jiang, Y. (1998). Contextual Cueing : Implicit Learning and Memory of Visual Context Guides Spatial Attention, *71*(36), 28–71. http://doi.org/10.1006/cogp.1998.0681

Clark, C. M., Lawlor-savage, L., & Goghari, V. M. (2017). Working memory training in healthy young adults : Support for the null from a randomized comparison to active and passive control groups. *PLoS ONE*, *12*(5). http://doi.org/10.1371/journal.pone.0177707

Clarke, P. J. F., Browning, M., Hammond, G., Notebaert, L., & MacLeod, C. (2014). The causal role of the dorsolateral prefrontal cortex in the modification of attentional bias: Evidence from transcranial direct current stimulation. *Biological Psychiatry*, *76*(12), 946–952. http://doi.org/10.1016/j.biopsych.2014.03.003

Cogmed Working Memory Training. (2015). Retrieved from http://www.cogmed.com/

D'Zmura, M. (1991). Color in visual search. *Vision Research*, *31*(6), 951–966. http://doi.org/10.1016/0042-6989(91)90203-H

Davies, D. R., & Parasuraman, R. (1982). *The Psychology of Vigilance*. London: Academic Press.

Dayan, E., Censor, N., Buch, E. R., Sandrini, M., & Cohen, L. G. (2013). Noninvasive brain stimulation: from physiology to network dynamics and back. *Nature Neuroscience*, *16*(7), 838–844. http://doi.org/10.1038/nn.3422

Dedoncker, J., Brunoni, A. R., Baeken, C., & Vanderhasselt, M.-A. (2016). The effect of the interval-between-sessions on prefrontal transcranial direct current stimulation (tDCS) on cognitive outcomes: A systematic review and meta-analysis. *Journal of Neural Transmission*, *123*(10), 1159-1172. http://doi.org/10.1007/s00702-016-1558-x

Derakshan, N., & Eysenck, M. W. (2009). Anxiety, Processing Efficiency, and Cognitive Performance. *European Psychologist*, *14*(2), 168–176. http://doi.org/10.1027/1016-9040.14.2.168

Derakshan, N., Smyth, S., & Eysenck, M. W. (2009). Effects of state anxiety on performance using a task-switching paradigm: An investigation of attentional control theory. *Psychonomic Bulletin & Review*, *16*(6), 1112–1117. http://doi.org/10.3758/PBR.16.6.1112

Derryberry, D., & Reed, M. a. (2002). Anxiety-related attentional biases and their regulation by attentional control. *Journal of Abnormal Psychology*, *111*(2), 225–236. http://doi.org/10.1037//0021-843X.111.2.225

Donnelly, N., Cave, K. R., Welland, M., & Menneer, T. (2006). Breast screening, chicken sexing and the search for oil: challenges for visual cognition. *Geological Society, London, Special Publications*, *254*(1), 43–55. http://doi.org/10.1144/gsl.sp.2006.254.01.04

Dougherty, M. R., Hamovitz, T., & Tidwell, J. W. (2015). Reevaluating the effectiveness of n-back training on transfer through the Bayesian lens: Support for the null. *Psychonomic Bulletin & Review*. http://doi.org/10.3758/s13423-015-0865-9

Drew, T., Boettcher, S., & Wolfe, J. M. (2016). Searching while loaded: Visual working memory does not interfere with hybrid search efficiency but hybrid search uses working memory capacity. *Psychonomic Bulletin and Review*, *23*(1), 201–212. http://doi.org/10.1016/j.addr.2015.05.001.An

Drew, T., Võ, M. L.-H., & Wolfe, J. M. (2013). The Invisible Gorilla Strikes Again: Sustained Inattentional Blindness in Expert Observers. *Psychological Science*, *24*(9), 1848–1853. http://doi.org/10.1177/0956797613479386

Druker, M., & Anderson, B. (2010). Spatial probability aids visual stimulus discrimination. *Frontiers in Human Neuroscience*, *4*. http://doi.org/10.3389/fnhum.2010.00063

Dugas, M. J., Freeston, M. H., & Ladouceur, R. (1997). Intolerance of uncertainty and problem orientation in worry. *Cognitive Therapy and Research*, *21*(6), 593–606. http://doi.org/10.1023/A:1021890322153

Duncan, J. (1980). The Locus of Interference in the Perception fo Simultaneous Stimuli.

Eckstein, M. (2011). Visual search: A retrospective. *Journal of Vision*, *11*, 1–36. http://doi.org/10.1167/11.5.14.

Eddy, C. M., Shapiro, K., Clouter, A., Hansen, P. C., & Rickards, H. E. (2017). Transcranial direct current stimulation can enhance working memory in Huntington's disease. *Progress in Neuro-Psychopharmacology and Biological Psychiatry*, *77*, 75–82. http://doi.org/10.1016/j.pnpbp.2017.04.002

Endres, M. J., Rickert, M. E., Bogg, T., Lucas, J., & Finn, P. R. (2011). Externalizing psychopathology and behavioral disinhibition: Working memory mediates signal discriminability and reinforcement moderates response bias in approach–avoidance learning. *Journal of Abnormal Psychology*, *120*(2), 336–351.

http://doi.org/10.1037/a0022501

Eriksen, C. W. (1952). Location of objects in a visual display as a function of the number of dimensions on which the objects differ. *Journal of Experimental Psychology*, *44*(1), 56–60. Retrieved from http://psycnet.apa.org/journals/xge/44/1/56.pdf

Eriksen, C. W. (1953). Object location in a complex perceptual field. *Journal of Experimental Psychology*, *45*(2), 126–132. Retrieved from http://psycnet.apa.org/journals/xge/45/2/126.pdf

Eysenck, M. W., & Calvo, M. G. (1992). Anxiety and Performance: The Processing Efficiency Theory. *Cognition & Emotion*, *6*(6), 409–434. http://doi.org/10.1080/02699939208409696

Eysenck, M. W., & Derakshan, N. (1998). Working Memory Capacity in High Trait-anxious and Repressor Groups. *Cognition & Emotion*, *12*(5), 697–713. http://doi.org/10.1080/026999398379501

Eysenck, M. W., & Derakshan, N. (2011). New perspectives in attentional control theory. *Personality and Individual Differences*, *50*(7), 955–960. http://doi.org/10.1016/j.paid.2010.08.019

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: attentional control theory. *Emotion, 7*(2), 336–353. http://doi.org/10.1037/1528-3542.7.2.336

Eysenck, M. W., Payne, S., & Derakshan, N. (2005). Trait anxiety, visuospatial processing, and working memory. *Cognition & Emotion*, *19*(8), 1214–1228. http://doi.org/10.1080/02699930500260245

Falcone, B., Coffman, B., Clark, V. P., & Parasuraman, R. (2012). Transcranial direct current stimulation augments perceptual sensitivity and 24-hour retention in a complex threat detection task. *PLoS ONE*, *7*(4). http://doi.org/10.1371/journal.pone.0034993

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience*, *14*(3), 340–347. http://doi.org/10.1162/089892902317361886

Fan, J., McCandliss, B., Fossella, J., Flombaum, J., & Posner, M. I. (2005). The activation of attentional networks. *NeuroImage*, *26*(2), 471–479. http://doi.org/10.1016/j.neuroimage.2005.02.004

Fecteau, S., Knoch, D., Fregni, F., Sultani, N., Boggio, P. S., & Pascual-Leone, A. (2007). Diminishing risk-taking behavior by modulating activity in the prefrontal cortex: a direct current stimulation study. *The Journal of Neuroscience*, *27*(46), 12500–12505. http://doi.org/10.1523/JNEUROSCI.3283-07.2007

Fecteau, S., Pascual-Leone, A., Zald, D. H., Liguori, P., Théoret, H., Boggio, P. S., & Fregni, F. (2007). Activation of prefrontal cortex by transcranial direct current stimulation reduces appetite for risk during ambiguous decision making. *The Journal of Neuroscience, 27*(23), 6212–6218. http://doi.org/10.1523/JNEUROSCI.0314-07.2007

Fergus, T. A., Bardeen, J. R., & Wu, K. D. (2013). Intolerance of Uncertainty and Uncertainty-Related Attentional Biases: Evidence of Facilitated Engagement or Disengagement Difficulty? *Cognitive Therapy and Research*, *37*(4), 735–741. http://doi.org/10.1007/s10608-012-9509-9

Fergus, T. A., & Carleton, N. R. (2016). Intolerance of uncertainty and attentional networks: Unique associations with alerting. *Journal of Anxiety Disorders*, *41*, 59–64.

http://doi.org/10.1016/j.janxdis.2016.03.010

Findlay, J. M., & Gilchrist, I. D. (2003). Eye Guidance and Visual Search. In G. Underwood (Ed.), *Cognitive Processes in Eye Guidance* (pp. 1–22). Oxford: Oxford University Press.

Findlay, J. M., & Walker, R. (1999). A model of saccade generation based on parallel processing and competitive inhibition. *The Behavioral and Brain Sciences*, *22*(4), 661-674. http://dx.doi.org/10.1017/S0140525X99002150

Fleck, M. S., & Mitroff, S. R. (2007). Rare targets are rarely missed in correctable search. *Psychological Science*, *18*(11), 943–947. http://doi.org/10.1111/j.1467-9280.2007.02006.x

Fleck, M. S., Samei, E., & Mitroff, S. R. (2010). Generalized "Satisfaction of Search": Adverse Influences on Dual-Target Search Accuracy, *16*(1), 60–71. http://doi.org/10.1037/a0018629.Generalized

Fletcher, R. (1998). *The City University Colour Vision Test* (3rd ed.). London: Keeler.

Fregni, F., Boggio, P. S., Nitsche, M. A., Bermpohl, F., Antal, A., Feredoes, E., Marcolin, M. A., Rigonatti, S. P., Silva, M. T. A., Paulus, W., & Pascual-Leone, A. (2005). Anodal transcranial direct current stimulation of prefrontal cortex enhances working memory. *Experimental Brain Research*, *166*(1), 23–30. http://doi.org/10.1007/s00221-005-2334-6

Fregni, F., Boggio, P. S., Nitsche, M. A., Rigonatti, S. P., & Pascual-Leone, A. (2006). Cognitive effects of repeated sessions of transcranial direct current stimulation in patients with depression. *Depression and Anxiety*, *23*, 482–484. http://doi.org/10.1007/s00221-005-2334-6

Fukuda, K., & Vogel, E. K. (2011). Individual differences in recovery time from attentional capture. *Psychological Science*, *22*(3), 361–368. http://doi.org/10.1177/0956797611398493

Gaspar, J. M., Christie, G. J., Prime, D. J., Jolicœur, P., & McDonald, J. J. (2016). Inability to suppress salient distractors predicts low visual working memory capacity. *Proceedings of the National Academy of Sciences*, *113*(13), 3696–3698. http://doi.org/10.1073/pnas.1523471113

Geng, J. J., & Behrmann, M. (2005). Spatial probability as an attentional cue in visual search. *Perception & Psychophysics*, *67*(7), 1252–1268. http://doi.org/10.3758/BF03193557

Gerdes, A. B. M., Alpers, G. W., & Pauli, P. (2008). When spiders appear suddenly: Spider-phobic patients are distracted by task-irrelevant spiders. *Behaviour Research and Therapy*, *46*(2), 174–187. http://doi.org/10.1016/j.brat.2007.10.010

Godwin, H. J., Hout, M. C., & Menneer, T. (2014). Visual similarity is stronger than semantic similarity in guiding visual search for numbers. *Psychonomic Bulletin & Review*, *21*(3), 689–695. http://doi.org/10.3758/s13423-013-0547-4

Godwin, H. J., Menneer, T., Cave, K. R., & Donnelly, N. (2010). Dual-target search for high and low prevalence X-ray threat targets. *Visual Cognition*, *18*(10), 1439–1463. http://doi.org/10.1080/13506285.2010.500605

Godwin, H. J., Menneer, T., Cave, K. R., Helman, S., Way, R. L., & Donnelly, N. (2010). The impact of Relative Prevalence on dual-target search for threat items from airport X-ray screening. *Acta Psychologica*, *134*(1), 79–84. http://doi.org/10.1016/j.actpsy.2009.12.009

Godwin, H. J., Menneer, T., Riggs, C. A., Cave, K. R., & Donnelly, N. (2015). Perceptual failures in the selection and identification of low-prevalence targets in relative prevalence visual search. *Attention, Perception & Psychophysics*, *77*(1), 150-159. http://doi.org/10.3758/s13414-014-0762-8

Goodwin, H., Yiend, J., & Hirsch, C. R. (2017). Generalized Anxiety Disorder, worry and attention to threat: A systematic review. *Clinical Psychology Review*, *54*, 107–122. http://doi.org/10.1016/j.cpr.2017.03.006

Gorbunova, E. S. (2017). Perceptual similarity in visual search for multiple targets. *Acta Psychologica*, *173*, 46–54. http://doi.org/10.1016/j.actpsy.2016.11.010

Gözenman, F., & Berryhill, M. E. (2016). Working memory capacity differentially influences responses to tDCS and HD-tDCS in a retro-cue task. *Neuroscience Letters*, *629*, 105–109. http://doi.org/10.1016/j.neulet.2016.06.056

Green, B., & Anderson, L. (1956). Color coding in a visual search task. *Journal of Experimental Psychology*, *51*(1). http://doi.org/10.1037/h0047484

Greenlee, E. T., Funke, G. J., Warm, J. S., Sawyer, B. D., Finomore, V. S., Mancuso, V. F., Funke, M. E., & Matthews, G. (2016). Stress and Workload Profiles of Network Analysis: Not All Tasks Are Created Equal. In D. Nicholson (Ed.), *Advances in Human Factors in Cybersecurity, 501* (pp. 153–166). http://doi.org/10.1007/978-3-319-41932-9_13

Greenwood, P. M., & Parasuraman, R. (2016). The Mechanisms of Far Tranfer From Cognitive Training: Review and Hypothesis. *Neuropsychology*, *30*(6), 742–755. http://doi.org/http://dx.doi.org/10.1037/neu0000235

Grillon, C., Robinson, O. J., Mathur, A., & Ernst, M. (2016). Effect of attention control on sustained attention during induced anxiety. *Cognition & Emotion*, *30*(4), 700-712. http://doi.org/10.1080/02699931.2015.1024614

Gunseli, E., Meeter, M., & Olivers, C. N. L. (2014). Is a search template an ordinary working memory? Comparing electrophysiological markers of working memory maintenance for visual search and recognition. *Neuropsychologia*, *60*(1), 29–38. http://doi.org/10.1016/j.neuropsychologia.2014.05.012

Hadwin, J. A., Visu-Petra, L., Muris, P., Derakshan, N., & MacLeod, C. (2016). Introduction to the Special Issue: Understanding the Role of Attentional Control in the Development of Anxiety in Childhood, Adolescence and Across the Lifespan. *Journal of Experimental Psychopathology*, *7*(3), 277–295.

Han, S. W., & Kim, M.-S. (2009). Do the contents of working memory capture attention? Yes, but cognitive control matters. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(5), 1292–1302. http://doi.org/10.1167/7.9.682

Harris, D., Noguchi, Y., Shimada, K., Ohsuga, M., Kamakura, Y., & Inoue, Y. (2015). Prevalence Effects in X-Ray Screening Tasks with a Static or Dynamic Visual Display: Is There Any Difference? In D. Harris (Ed.), *Engineering Psychology and Cognitive Ergonomics, EPCE 2015, Lecture Notes In Computer Science, 9174* (pp. 77–83). http://doi.org/10.1007/978-3-642-02728-4

Harrison, T. L., Shipstead, Z., Hicks, K. L., Hambrick, D. Z., Redick, T. S., & Engle, R. W. (2013). Working Memory Training May Increase Working Memory Capacity but Not Fluid Intelligence. *Psychological Science*, *24*(12), 2409–2419. http://doi.org/10.1177/0956797613492984

Helton, W. S., & Russell, P. N. (2011). Feature absence-presence and two theories of lapses of sustained attention. *Psychological Research*, *75*(5), 384–92.

http://doi.org/10.1007/s00426-010-0316-1

Hepsomali, P., Hadwin, J. A., Liversedge, S. P., & Garner, M. (2017). Pupillometric and saccadic measures of affective and executive processing in anxiety. *Biological Psychology*, *127*, 173–179. http://doi.org/10.1016/j.biopsycho.2017.05.013

Hill, A. T., Fitzgerald, P. B., & Hoy, K. E. (2016). Effects of Anodal Transcranial Direct Current Stimulation on Working Memory: A Systematic Review and Meta-Analysis of Findings from Healthy and Neuropsychiatric Populations. *Brain Stimulation*, *9*(2), 197–208. http://doi.org/10.1016/j.brs.2015.10.006

Hillstrom, a P., & Yantis, S. (1994). Visual motion and attentional capture. *Perception & Psychophysics*, *55*(4), 399–411. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/8036120

Hollingworth, A., & Luck, S. J. (2009). The Role of Visual Working Memory in the Control of Gaze during Visual Search. *Attention, Perception, & Psychophysics*, *71*(4), 936–949. http://doi.org/10.3758/APP.71.4.936.The

Holmes, J., Byrne, E. M., Gathercole, S. E., & Ewbank, M. P. (2016). Transcranial Random Noise Stimulation Does Not Enhance the Effects of Working Memory Training. *Journal of Cognitive Neuroscience*, *28*(10), 1471–1483. http://doi.org/10.1162/jocn

Horowitz, T. S. (2017). Prevalence in Visual Search: From the Clinic to the Lab and Back Again. *Japanese Psychological Research*, *59*(2), 65–108. http://doi.org/10.1111/jpr.12153

Horowitz, T. S., & Wolfe, J. M. (1998). Visual search has no memory. *Nature*, *394*(6693), 575–7. http://doi.org/10.1038/29068

Horowitz, T. S., & Wolfe, J. M. (2003). Memory for rejected distractors in visual search? *Visual Cognition*, *10*(3), 257–298. http://doi.org/10.1080/13506280143000005

Horvath, J. C., Carter, O., & Forte, J. D. (2014). Transcranial direct current stimulation: five important issues we aren't discussing (but probably should be). *Frontiers in Systems Neuroscience*, *8*. http://doi.org/10.3389/fnsys.2014.00002

Horvath, J. C., Forte, J. D., & Carter, O. (2015a). Evidence that transcranial direct current stimulation (tDCS) generates little-to-no reliable neurophysiologic effect beyond MEP amplitude modulation in healthy human subjects: A systematic review. *Neuropsychologia*. http://doi.org/10.1016/j.neuropsychologia.2014.11.021

Horvath, J. C., Forte, J. D., & Carter, O. (2015b). Quantitative review finds no evidence of cognitive effects in healthy populations from single-session transcranial direct current stimulation (tDCS). *Brain Stimulation*, *8*(3), 535–550. http://doi.org/10.1016/j.brs.2015.01.400

Hout, M. C., & Goldinger, S. D. (2015). Target templates: the precision of mental representations affects attentional guidance and decision-making in visual search. *Attention, Perception, & Psychophysics*, *77*(1), 128–149. http://doi.org/10.1016/j.surg.2006.10.010.Use

Howard, C. J., Troscianko, T., & Gilchrist, I. D. (2010). Europe PMC Funders Group Eye-response lags during a continuous monitoring task, *17*(5), 710–717. http://doi.org/10.3758/PBR.17.5.710.Eye-response

Howard, C. J., Troscianko, T., Gilchrist, I. D., Behera, A., & Hogg, D. C. (2013). Suspiciousness perception in dynamic scenes: a comparison of CCTV operators and novices. *Frontiers in Human Neuroscience*, *7*. http://doi.org/10.3389/fnhum.2013.00441

Hsu, T., Juan, C., & Tseng, P. (2016). Individual Differences and State-Dependent Responses in Transcranial Direct Current Stimulation. *Frontiers in Human Neuroscience*, *10*. http://doi.org/10.3389/FNHUM.2016.00643

Hulleman, J. (2009). No need for inhibitory tagging of locations in visual search. *Psychonomic Bulletin & Review*, *16*(1), 116–120. http://doi.org/10.3758/PBR.16.1.116

Hulleman, J., & Olivers, C. N. L. (2014). Search through complex motion displays does not break down under spatial memory load. *Psychonomic Bulletin & Review*, *21*(3), 652-658. http://doi.org/10.3758/s13423-013-0537-6

Hulleman, J., & Olivers, C. N. L. (2017). The impending demise of the item in visual search. *Behavioral and Brain Sciences*, *40*. http://doi.org/10.1017/S0140525X15002794

Hulme, C., & Melby-Lervåg, M. (2012). Current evidence does not support the claims made for CogMed working memory training. *Journal of Applied Research in Memory and Cognition*, *1*(3), 197–200. http://doi.org/10.1016/j.jarmac.2012.06.006

Irons, J. L., Folk, C. L., & Remington, R. W. (2012). All set! Evidence of simultaneous attentional control settings for multiple target colors. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(3), 758–775. http://doi.org/10.1037/a0026578

Itti, L., & Koch, C. (2000). A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision Research*, *40*(10–12), 1489–1506. http://doi.org/10.1016/S0042-6989(99)00163-7

Ivry, R. B., & Cohen, A. (1992). Asymmetry in visual search for targets defined by differences in movement speed. *Journal of Experimental Psychology: Human Perception and Performance*, *18*(4), 1045–1057. http://doi.org/10.1037/0096-1523.18.4.1045

Iyer, M. B., Mattu, U., Grafman, J., Lomarev, M., Sato, S., & Wassermann, E. M. (2005). Safety and cognitive effect of frontal DC brain polarization in healthy individuals. *Neurology*, *64*(5), 872–875. http://doi.org/10.1212/01.WNL.0000152986.07469.E9

Jaeggi, S. M., Buschkuehl, M., Etienne, A., Ozdoba, C., Perrig, W. J., & Nirkko, A. C. (2007). On how high performers keep cool brains in situations of cognitive overload. *Cognitive, Affective & Behavioral Neuroscience*, *7*(2), 75–89. http://doi.org/10.3758/CABN.7.2.75

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(19), 6829–6833. http://doi.org/10.1073/pnas.0801268105

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Shah, P. (2012). Cogmed and working memory training—Current challenges and the search for underlying mechanisms. *Journal of Applied Research in Memory and Cognition*, *1*(3), 211–213. http://doi.org/10.1016/j.jarmac.2012.07.002

Jardine, N. L., & Moore, C. M. (2015). Losing the Trees for the Forest in Dynamic Visual Search. *Journal of Experimental Psychology: Human Perception and Performance*, *42*(5), 617–630. http://doi.org/10.1037/xhp0000186

Jonides, J., & Yantis, S. (1988). Uniqueness of abrupt visual onset in capturing attention. *Perception & Psychophysics*, *43*(4), 346–354. http://doi.org/10.3758/BF03208805

Kane, M. J., Bleckley, M. K., Conway, A. R. A., & Engle, R. W. (2001). A Controlled-Attention View of Working-Memory Capacity. *Journal of Experimental Psychology: General*, *130*(2), 169–183. http://doi.org/10.1037/0096-3445.130.2.169

Kane, M. J., Poole, B. J., Tuholski, S. W., & Engle, R. W. (2006). Working memory capacity and the top-down control of visual search: Exploring the boundaries of "executive attention". *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *32*(4), 749–777. http://doi.org/10.1037/0278-7393.32.4.749

Kaplan, I. T., & Carvellas, T. (1965). Scanning for multiple targets. *Perceptual and Motor Skills, 21*(1), 239–243. http://doi.org/10.2466/pms.1965.21.1.239

Keeser, D., Padberg, F., Reisinger, E., Pogarell, O., Kirsch, V., Palm, U., Karch, S., Möller, H.-J., Nitsche, M. A., & Mulert, C. (2011). Prefrontal direct current stimulation modulates resting EEG and event-related potentials in healthy subjects: a standardized low resolution tomography (sLORETA) study. *NeuroImage*, *55*(2), 644–657. http://doi.org/10.1016/j.neuroimage.2010.12.004

Khawaja, N., & Yu, L. (2010). A comparison of the 27-item and 12-item intolerance of uncertainty scales. *Clinical Psychologist*, *14*(3), 97-106. http://doi.org/10.1080/13284207.2010.502542

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching—A review. *Psychological Bulletin*, *136*(5), 849–874. http://doi.org/10.1037/a0019842

Kincses, T. Z., Antal, A., Nitsche, M. A., Bártfai, O., & Paulus, W. (2004). Facilitation of probabilistic classification learning by transcranial direct current stimulation of the prefrontal cortex in the human. *Neuropsychologia*, *42*(1), 113–117. http://doi.org/10.1016/S0028-3932(03)00124-6

Klein, R. M. (1988). Inhibitory tagging system facilitates visual search. *Nature*, *334,* 430-431. http://doi.org/10.1038/334430a0

Klein, R. M. (2000). Inhibition of return. *Trends in Cognitive Sciences*, *4*(4), 138–147. http://doi.org/10.1016/S1364-6613(00)01452-2

Klein, R. M., & Farrell, M. (1989). Search performance without eye movements. *Perception & Psychophysics*, *46*(5), 476–482. http://dx.doi.org/10.3758/BF03210863

Klein, R. M., & MacInnes, W. J. (1999). Inhibition of Return is a Foraging Facilitator in Visual Search. *Psychological Science*, *10*(4), 346–352. http://doi.org/10.1111/1467-9280.00166

Klingberg, T. (2010). Training and plasticity of working memory. *Trends in Cognitive Sciences*, *14*(7), 317–324. http://doi.org/10.1016/j.tics.2010.05.002

Klingberg, T. (2012). Is working memory capacity fixed? *Journal of Applied Research in Memory and Cognition*, *1*(3), 194–196. http://doi.org/10.1016/j.jarmac.2012.07.004

Klingberg, T., Forssberg, H., & Westerberg, H. (2002). Training of working memory in children with ADHD. *Journal of Clinical and Experimental Neuropsychology*, *24*(6), 781–791. http://doi.org/10.1076/jcen.24.6.781.8395

Koerner, N., & Dugas, M. J. (2008). *A Cognitive Model of Generalized Anxiety Disorder: The Role of Intolerance of Uncertainty*. In G. C. L. Davey & A. Wells (Eds.), *Worry and its Psychological Disorders: Theory, Assessment and Treatment* (pp. 201-216). http://doi.org/10.1002/9780470713143.ch12

Körner, C., & Gilchrist, I. D. (2008). Memory processes in multiple-target visual search. *Psychological Research*, *72*(1), 99–105. http://doi.org/10.1007/s00426-006-0075-1

Kristjánsson, Á. (2015). Reconsidering Visual Search. *I-Perception*, *6*(6), 1–14.

http://doi.org/10.1177/2041669515614670

Krohne, H. W., & Hock, M. (2011). Anxiety, coping strategies, and the processing of threatening information: Investigations with cognitive-experimental paradigms. *Personality and Individual Differences*, *50*(7), 916–925. http://doi.org/10.1016/j.paid.2010.08.001

Kunar, M. a, & Watson, D. G. (2011). Visual search in a multi-element asynchronous dynamic (MAD) world. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(4), 1017–1031. http://doi.org/10.1037/a0023093

Kunar, M. a, & Watson, D. G. (2014). When are abrupt onsets found efficiently in complex visual search? Evidence from multielement asynchronous dynamic search. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(1), 232–252. http://doi.org/10.1037/a0033544

Kundel, H. L., & La Follette, P. S. (1972). Visual Search Patterns and Experience with Radiological Images. *Radiology*, *103*(3), 523–528. http://doi.org/10.1148/103.3.523

Lam, R. W., Michalak, E. E., & Swinson, R. P. (2006). Assessment scales in depression, mania, and anxiety. *The Psychiatrist*, *30*(10), 398. http://doi.org/10.1192/pb.30.10.398

Lara, A. H., & Wallis, J. D. (2015). The Role of Prefrontal Cortex in Working Memory: A Mini Review. *Frontiers in Systems Neuroscience*, *9*. http://doi.org/10.3389/fnsys.2015.00173

Lavie, N. (2006). The role of perceptual load in visual awareness. *Brain Research*, *1080*(1), 91–100. http://doi.org/10.1016/j.brainres.2005.10.023

Lavie, N., Beck, D. M., & Konstantinou, N. (2014). Blinded by the load: attention , awareness and the role of perceptual load. *Philosophical Transactions of the Royal*

Society B: Biological Sciences, *369*(1641). http://doi.org/10.1098/rstb.2013.0205

Litchfield, D., Ball, L. J., Donovan, T., Manning, D. J., & Crawford, T. (2010). Viewing another person's eye movements improves identification of pulmonary nodules in chest x-ray inspection. *Journal of Experimental Psychology: Applied*, *16*(3), 251–262. http://doi.org/10.1037/a0020082

Lleras, A., & Von Mühlenen, A. (2004). Spatial context and top-down strategies in visual search. *Spatial Vision*, *17*(4–5), 465–482. http://doi.org/10.1163/1568568041920113

Luhmann, C. C., Chun, M. M., Yi, D.-J., Lee, D., & Wang, X.-J. (2008). Neural dissociation of delay and uncertainty in intertemporal choice. *The Journal of Neuroscience*, *28*(53), 14459–14466. http://doi.org/10.1523/JNEUROSCI.5058-08.2008

Luhmann, C. C., Ishida, K., & Hajcak, G. (2011). Intolerance of uncertainty and decisions about delayed, probabilistic rewards. *Behavior Therapy*, *42*(3), 378–386. http://doi.org/10.1016/j.beth.2010.09.002

Mackenzie, A., & Harris, J. (2015). Using Experts' Eye Movements to Influence Scanning Behaviour in Novice Drivers. *Journal of Vision*, *15*(12), 367. http://doi.org/10.1167/15.12.367

Mackworth, N. H. (1948). The breakdown of vigilance durning prolonged visual search. *Quarterly Journal of Experimental Psychology*, *1*(1), 6–21. http://doi.org/10.1080/17470214808416738

MacLeod, C., & Donnellan, A. M. (1993). Individual differences in anxiety and the restriction of working memory capacity. *Personality and Individual Differences*, *15*(2), 163–173. http://doi.org/10.1016/0191-8869(93)90023-V

Macmillan, N. A., & Creelman, C. D. (2009). *Detection Theory: A User's Guide.* Mawah, New Jersey: Lawrence Erlbaum Associates.

Manly, T., Robertson, I., Galloway, M., & Hawkins, K. (1999). The absent mind:: further investigations of sustained attention to response. *Neuropsychologia 37*(6), 661-670. https://doi.org/10.1016/S0028-3932(98)00127-4

Maraver, M. J., Bajo, M. T., & Gomez-Ariza, C. J. (2016). Training on Working Memory and Inhibitory Control in Young Adults. *Frontiers in Human Neuroscience*, *10*. http://doi.org/10.3389/fnhum.2016.00588

Mathews, A., May, J., Mogg, K., & Eysenck, M. W. (1990). Attentional bias in anxiety: selective search or defective filtering? *Journal of Abnormal Psychology*, *99*(2), 166–173. http://dx.doi.org/10.1037/0021-843X.99.2.166

McKinley, R. A., McIntire, L., Bridges, N., Goodyear, C., & Weisend, M. P. (2013). Acceleration of image analyst training with transcranial direct current stimulation. *Behavioral Neuroscience*, *127*(6), 936–946. http://doi.org/10.1037/a0034975

Mcvay, J. C., & Kane, M. J. (2012). Why Does Working Memory Capacity Predict Variation in Reading Comprehension? On the Influence of Mind Wandering and Executive Attention. *Journal of Experimental Psychology: General*, *141*(2), 302–320. http://doi.org/10.1037/a0025250.Why

Meiran, N. (2000). Modeling cognitive control in task-switching. *Psychological Research*, *63*(3–4), 234–249. http://doi.org/10.1007/s004269900004

Meiran, N., Chorev, Z., & Sapir, A. (2000). Component Processes in Task Switching. *Cognitive Psychology*, *41*(3), 211–253. http://doi.org/10.1006/cogp.2000.0736

Melby-Lervåg, M., & Hulme, C. (2015a). There is no convincing evidence that working memory training is effective: A reply to Au et al. (2014) and Karbach and Verhaeghen (2014). *Psychonomic Bulletin & Review*, (2014). http://doi.org/10.3758/s13423-015-0862-z

Melby-Lervåg, M., & Hulme, C. (2015b). There is no convincing evidence that working memory training is effective: A reply to Au et al. (2014) and Karbach and Verhaeghen (2014). *Psychonomic Bulletin & Review*. http://doi.org/10.3758/s13423-015-0862-z

Menneer, T., Barrett, D. J. K., Phillips, L., Donnelly, N., & Cave, K. R. (2007). Costs in searching for two targets: dividing search across target types could improve airport security screening. *Applied Cognitive Psychology*, *21*(7), 915–932. http://doi.org/10.1002/acp.1305

Menneer, T., Cave, K. R., & Donnelly, N. (2009). The cost of search for multiple targets: effects of practice and target similarity. *Journal of Experimental Psychology: Applied*, *15*(2), 125–39. http://doi.org/10.1037/a0015331

Menneer, T., Phillips, L., Donnelly, N., Barrett, D. J. K., & Cave, K. R. (2004). Search efficiency for multiple targets. *Cognitive Technology*, *9*(2), 22–25.

Menneer, T., Stroud, M. J., Cave, K. R., Donnelly, N., & Rayner, K. (2008). Eye movements in search for multiple targets. In K. Rayner, D. Shen, X. Bai, & G. Yan (Eds.), *Cognitive and Cultural Influences on Eye Movements* (pp. 171-180). London: Psychology Press.

Miler, J. A., Meron, D., Baldwin, D. S., & Garner, M. (2017). The Effect of Prefrontal Transcranial Direct Current Stimulation on Attention Network Function in Healthy Volunteers. *Neuromodulation: Technology at the Neural Interface*. http://doi.org/10.1111/ner.12629

Mitroff, S. R., & Biggs, A. T. (2014). The Ultra-Rare-Item Effect: Visual Search for Exceedingly Rare Items Is Highly Susceptible to Error. *Psychological Science*, *25*(1), 284-289. http://doi.org/10.1177/0956797613504221

Mogg, K., Mathews, A., Bird, C., & Macgregor-Morris, R. (1990). Effects of stress and anxiety on the processing of threat stimuli. *Journal of Personality and Social Psychology*, *59*(6), 1230–1237. http://doi.org/10.1037/0022-3514.59.6.1230

Monsell, S. (2003). Task switching. *Trends in Cognitive Sciences*, *7*(3), 134–140. http://doi.org/10.1016/S1364-6613(03)00028-7

Morrison, A. B., & Chein, J. M. (2011). Does working memory training work? The promise and challenges of enhancing cognition by training working memory. *Psychonomic Bulletin & Review*, *18*(1), 46–60. http://doi.org/10.3758/s13423-010-0034-0

Mulquiney, P. G., Hoy, K. E., Daskalakis, Z. J., & Fitzgerald, P. B. (2011). Improving working memory: Exploring the effect of transcranial random noise stimulation and transcranial direct current stimulation on the dorsolateral prefrontal cortex. *Clinical Neurophysiology*, *122*(12), 2384-2389. http://doi.org/10.1016/j.clinph.2011.05.009

Neider, M. B., & Zelinsky, G. J. (2006). Scene context guides eye movements during visual search. *Vision Research*, *46*(5), 614–621. http://doi.org/10.1016/j.visres.2005.08.025

Neisser, U. (1963). Decision-time without reaction-time: Experiments in visual scanning. *The American Journal of Psychology, 76*(3), 376-385. http://doi.org/10.2307/1419778.

Neisser, U. (1964). Visual Search. *Scientific American*, *210*(6), 94–103.

Neisser, U., & Beller, H. (1965). Searching through word lists. *British Journal of Psychology, 56*(4), 349–358. http://doi.org/10.1111/j.2044-8295.1965.tb00977.x

Neisser, U., & Lazar, R. (1964). Searching for Novel Targets. *Perceptual and Motor Skills, 19*(2), 427–432. http://doi.org/10.2466/pms.1964.19.2.427

Neisser, U., Novick, R., & Lazar, R. (1963). Searching for ten targets simultaneously. *Perceptual and Motor Skills, 17*(3), 955-961. https://doi.org/10.2466/pms.1963.17.3.955

Neisser, U., & Stoper, A. (1965). Redirecting the search process. *British Journal of Psychology, 56*(4), 359-368. https://doi.org/10.1111/j.2044-8295.1965.tb00978.x

Nelson, J., McKinley, R. A., Phillips, C., McIntire, L., Goodyear, C., Camden, A., & Monforton, L. (2016). The Effects of Transcranial Direct Current Stimulation (tDCS) on Multitasking Throughput Capacity. *Frontiers in Human Neuroscience*, *10*. http://doi.org/10.3389/FNHUM.2016.00589

Nelson, J. T., McKinley, R. A., Golob, E. J., Warm, J. S., & Parasuraman, R. (2014). Enhancing vigilance in operators with prefrontal cortex transcranial direct current stimulation (tDCS). *NeuroImage*, *85*(3), 909–917. http://doi.org/10.1016/j.neuroimage.2012.11.061

Nitsche, M. A., Cohen, L. G., Wassermann, E. M., Priori, A., Lang, N., Antal, A., Paulus, W., Hummel, F., Boggio, P. S., Fregni, F., & Pascual-Leone, A. (2008). Transcranial direct current stimulation: State of the art 2008. *Brain Stimulation*, *1*(3), 206–223. http://doi.org/10.1016/j.brs.2008.06.004

Nitsche, M. A., & Paulus, W. (2000). Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *The Journal of Physiology*, *527*

(3), 633–639. http://doi.org/10.1111%2Fj.1469-7793.2000.t01-1-00633.x

Nitsche, M. A., & Paulus, W. (2001). Sustained excitability elevations induced by transcranial DC motor cortex stimulation in humans. *Neurology*, *57*(10), 1899–1901. http://doi.org/10.1212/WNL.57.10.1899

Olesen, P. J., Westerberg, H., & Klingberg, T. (2004). Increased prefrontal and parietal activity after training of working memory. *Nature Neuroscience*, *7*(1), 75–79. http://doi.org/10.1038/nn1165

Oliveira, J. F., Zanão, T. a, Valiengo, L., Lotufo, P. a, Benseñor, I. M., Fregni, F., & Brunoni, A. R. (2013). Acute working memory improvement after tDCS in antidepressant-free patients with major depressive disorder. *Neuroscience Letters*, *537*, 60–64. http://doi.org/10.1016/j.neulet.2013.01.023

Olivers, C. N. L., Peters, J., Houtkamp, R., & Roelfsema, P. R. (2011). Different states in visual working memory: when it guides attention and when it does not. *Trends in Cognitive Sciences, 15*(7), 327–34. http://doi.org/10.1016/j.tics.2011.05.004

Owens, M., Koster, E. H. W., & Derakshan, N. (2012). Impaired filtering of irrelevant information in dysphoria: An ERP study. *Social Cognitive and Affective Neuroscience*, *7*(7), 752–763. http://doi.org/10.1093/scan/nsr050

Owens, M., Koster, E. H. W., & Derakshan, N. (2013). Improving attention control in dysphoria through cognitive training: transfer effects on working memory capacity and filtering efficiency. *Psychophysiology*, *50*(3), 297–307. http://doi.org/10.1111/psyp.12010

Owens, M., Stevenson, J., Hadwin, J. A., & Norgate, R. (2014). When does anxiety help or hinder cognitive test performance? The role of working memory capacity. *British*

Journal of Psychology, *105*(1), 92–101. http://doi.org/10.1111/bjop.12009

Pacheco-Unguetti, A. P., Acosta, A., Lupiáñez, J., Román, N., & Derakshan, N. (2012). Response inhibition and attentional control in anxiety. *The Quarterly Journal of Experimental Psychology*, *65*, 646–660. http://doi.org/10.1080/17470218.2011.637114

Parasuraman, R. (1979). Memory load and event rate control sensitivity decrements in sustained attention. *Science, 205*(4409), 924-927. http://doi.org/10.1126/science.472714

Parasuraman, R., & McKinley, R. A. (2014). Using Noninvasive Brain Stimulation to Accelerate Learning and Enhance Human Performance. *Human Factors: The Journal of the Human Factors and Ergonomics Society 56*(5), 816-824. http://doi.org/10.1177/0018720814538815

Pashler, H. (2000). Task switching and multitask performance. In S. Monsell & J. Driver (Eds.), *Attention and Performance XVIII: Control of Cognitive Processes* (pp. 277–307). Cambridge, MA: MIT Press.

Peltier, C., & Becker, M. W. (2016). Working Memory Capacity Predicts Selection and Identification Errors in Visual Search. *Perception, 46*(1), 109-115. http://doi.org/10.1177/0301006616678421

Peltier, C., & Becker, M. W. (2017). Individual differences predict low prevalence visual search performance. *Cognitive Research: Principles and Implications*, *2*(5). http://doi.org/10.1186/s41235-016-0042-3

Pergolizzi, D., & Chua, E. F. (2017). Increased contextual cue utilization with tDCS over the prefrontal cortex during a recognition task. *Brain Research*, *1655*, 1–9.

http://doi.org/10.1016/j.brainres.2016.11.008

Peterson, M. S., Kramer, A. F., Wang, R. F., Irwin, D. E., & McCarley, J. S. (2001). Visual Search Has Memory. *Psychological Science*, *12*(4), 287–292. https://doi.org/10.1111/1467-9280.00353

Pinto, Y., Olivers, C. N. L., & Theeuwes, J. (2006). When is search for a static target among dynamic distractors efficient? *Journal of Experimental Psychology: Human Perception and Performance*, *32*(1), 59–72. http://doi.org/10.1037/0096-1523.32.1.59

Poreisz, C., Boros, K., Antal, A., & Paulus, W. (2007). Safety aspects of transcranial direct current stimulation concerning healthy subjects and patients. *Brain Research Bulletin*, *72*(4–6), 208–214. http://doi.org/10.1016/j.brainresbull.2007.01.004

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. http://doi.org/10.1080/00335558008248231

Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma & D. G. Bouwhuis (Eds.), *Attention and Performance X: Control of Language Processes* (pp. 531–556). London: Erlbaum.

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience*, *13*, 25–42. http://doi.org/10.1146/annurev.ne.13.030190.000325

Posner, M. I., & Rothbart, M. K. (2007). Research on Attention Networks as a Model for the Integration of Psychological Science. *Annual Review of Psychology*, *58*(1), 1–23. http://doi.org/10.1146/annurev.psych.58.110405.085516

Posner, M. I., Snyder, C. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology*, *109*(2), 160–174.

http://doi.org/10.1037/0096-3445.109.2.160

Proulx, M. J. (2011). Individual differences and metacognitive knowledge of visual search strategy. *PLoS ONE*, *6*(10). http://doi.org/10.1371/journal.pone.0027043

Rajsic, J., Sun, S. Z., Huxtable, L., Pratt, J., & Ferber, S. (2016). Pop-out and pop-in: Visual working memory advantages for unique items. *Psychonomic Bulletin & Review*, *23*(6), 1787–1793. http://doi.org/10.3758/s13423-016-1034-5

Ravizza, S. M., & Carter, C. S. (2008). Shifting set about task switching: Behavioral and neural evidence for distinct forms of cognitive flexibility. *Neuropsychologia*, *46*(12), 2924–2935. http://doi.org/10.1016/j.neuropsychologia.2008.06.006

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin*, *124*(3), 372–422. http://dx.doi.org/10.1037/0033-2909.124.3.372

Rich, A. N., Kunar, M. A., Wert, M. J. Van, Hidalgo-sotelo, B., Horowitz, T. S., & Wolfe, J. M. (2008). Why do we miss rare targets ? Exploring the boundaries of the low prevalence effect. *Journal of Vision*, *8*(15), 1–17. http://doi.org/10.1167/8.15.15

Richards, H. J., Benson, V., Donnelly, N., & Hadwin, J. A. (2014). Exploring the function of selective attention and hypervigilance for threat in anxiety. *Clinical Psychology Review*, *34*(1), 1–13. http://doi.org/10.1016/j.cpr.2013.10.006

Richards, H. J., Benson, V., & Hadwin, J. a. (2012). The attentional processes underlying impaired inhibition of threat in anxiety: the remote distractor effect. *Cognition & Emotion*, *26*(5), 934–942. http://doi.org/10.1080/02699931.2011.630990

Richards, H. J., Hadwin, J. A., Benson, V., Wenger, M., & Donnelly, N. (2011). The influence of anxiety on processing capacity for threat detection. *Psychonomic Bulletin*

& Review, *18*(5), 883–889. http://doi.org/10.3758/s13423-011-0124-7

Rosenberg, M., Noonan, S., DeGutis, J., & Esterman, M. (2011). Sustaining visual attention in the face of distraction: A novel gradual onset continuous performance task. *Journal of Vision*, *11*(11), 127–127. http://doi.org/10.1167/11.11.127

Rosenkranz, K., Nitsche, M. A., Tergau, F., & Paulus, W. (2000). Diminution of training-induced transient motor cortex plasticity by weak transcranial direct current stimulation in the human. *Neuroscience Letters*, *296*(1), 61–63. https://doi.org/10.1016/S0304-3940(00)01621-9

Rossi, A. F., Pessoa, L., Desimone, R., & Ungerleider, L. G. (2009). The prefrontal cortex and the executive control of attention. *Experimental Brain Research*, *192*(3), 489–497. http://doi.org/10.1007/s00221-008-1642-z.The

Roughan, L., & Hadwin, J. A. (2011). The impact of working memory training in young people with social, emotional and behavioural difficulties. *Learning and Individual Differences*, *21*(6), 759–764. http://doi.org/10.1016/j.lindif.2011.07.011

Ruf, S. P., Fallgatter, A. J., & Plewnia, C. (2017). Augmentation of working memory training by transcranial direct current stimulation (tDCS). *Scientific Reports*, *7*(1), 876. http://doi.org/10.1038/s41598-017-01055-1

Savelsbergh, G. J. P., Williams, A. M., Kamp, J. Van Der, & Ward, P. (2002). Visual search, anticipation and expertise in soccer goalkeepers. *Journal of Sports Sciences*, *20*(3), 279–287. http://doi.org/10.1080/026404102317284826

Schwaninger, A., Hardmeier, D., & Hofer, F. (2004). Measuring visual abilities and visual knowledge of aviation security screeners. *IEEE ICCST Proceedings*, 38, 258-264. doi:10.1109/CCST.2004.1405402

Schwaninger, A. (2016). Determinants of airport security X-ray screeners' detection performance. *Aviation Security International*, 22(4), 28–29.

Schwark, J. D., Sandry, J., & Dolgov, I. (2013). Evidence for a positive relationship between working-memory capacity and detection of low-prevalence targets in visual search. *Perception*, *42*(1), 112–114. http://doi.org/10.1068/p7386

Schwark, J. D., Sandry, J., Macdonald, J., & Dolgov, I. (2012). False feedback increases detection of low-prevalence targets in visual search. *Attention, Perception & Psychophysics*, *74*(8), 1583–9. http://doi.org/10.3758/s13414-012-0354-4

Schwartz, B., Ward, A., Monterosso, J., Lyubomirsky, S., White, K., & Lehman, D. R. (2002). Maximizing versus satisficing: Happiness is a matter of choice. *Journal of Personality and Social Psychology*, *83*(5), 1178–1197. http://doi.org/10.1037/0022-3514.83.5.1178

Shackman, A. J., Sarinopoulos, I., Maxwell, J. S., Pizzagalli, D. A., Lavric, A., & Davidson, R. J. (2006). Anxiety selectively disrupts visuospatial working memory. *Emotion*, *6*, 40–61. http://doi.org/10.1037/1528-3542.6.1.40

Shaw, T. H., Warm, J. S., Finomore, V., Tripp, L., Matthews, G., Weiler, E., & Parasuraman, R. (2009). Effects of sensory modality on cerebral blood flow velocity during vigilance. *Neuroscience Letters*, *461*(3), 207–11. http://doi.org/10.1016/j.neulet.2009.06.008

Sheehan, D., Janvas, J., Baker, R., Harnett-Sheehan, K., Knapp, E., Sheehan, M., Lecrubier, Y., Weiller, E., Hergueta, T., Amorim, P, Bonora, L. I., & Lépine, J. P. (2006). MINI International Neuropsychiatric Interview.

Shipstead, Z., Hicks, K. L., & Engle, R. W. (2012). Working memory training remains a work in progress. *Journal of Applied Research in Memory and Cognition*, *1*(3), 217–219. http://doi.org/10.1016/j.jarmac.2012.07.009

Shipstead, Z., Redick, T. S., & Engle, R. W. (2012). Is working memory training effective? *Psychological Bulletin*, *138*(4), 628–654. http://doi.org/10.1037/a0027473

Shore, D. I., & Klein, R. M. (2000). On the manifestations of memory in visual search. *Spatial Vision*, *14*(1), 59–75. http://dx.doi.org/10.1163/156856801741369

Silvanto, J., Muggleton, N., & Walsh, V. (2008). State-dependency in brain stimulation studies of perception and cognition. *Trends in Cognitive Sciences*, *12*(12), 447–454. http://doi.org/10.1016/j.tics.2008.09.004

Simon, A. J., Skinner, S. N., & Ziegler, D. A. (2016). Training Working Memory: Anatomy Matters. *Journal of Neuroscience*, *36*(30), 7805–7806. http://doi.org/10.1523/JNEUROSCI.1513-16.2016

Smirni, D., Turriziani, P., Mangano, G. R., Cipolotti, L., & Oliveri, M. (2015). Modulating Memory Performance in Healthy Subjects with Transcranial Direct Current Stimulation Over the Right Dorsolateral Prefrontal Cortex. *PLoS ONE*, *10*(12). http://doi.org/10.1371/journal.pone.0144838

Smith, P. L., Ratcliff, R., & Wolfgang, B. J. (2004). Attention orienting and the time course of perceptual decisions: Response time distributions with masked and unmasked displays. *Vision Research*, *44*(12), 1297–1320. http://doi.org/10.1016/j.visres.2004.01.002

Sobel, K. V., Puri, A. M., & Hogan, J. (2014). Target grouping in visual search for multiple digits. *Attention, Perception, & Psychophysics*, *77*(1), 67–77. http://doi.org/10.3758/s13414-014-0761-9

Sobel, K. V, Gerrie, M. P., Poole, B. J., & Kane, M. J. (2007). Individual differences in working memory capacity and visual search: the roles of top-down and bottom-up processing. *Psychonomic Bulletin & Review*, *14*(5), 840–845. http://doi.org/10.3758/BF03194109

Sörqvist, P., & Marsh, J. E. (2015). How Concentration Shields Against Distraction. *Current Directions in Psychological Science*, *24*(4), 267–272. http://doi.org/10.1177/0963721415577356

Soto, D., Hodsoll, J., Rotshtein, P., & Humphreys, G. W. (2008). Automatic guidance of attention from working memory. *Trends in Cognitive Sciences*, *12*(9), 342–8. http://doi.org/10.1016/j.tics.2008.05.007

Soto, D., Wriglesworth, A., Bahrami-Balani, A., & Humphreys, G. W. (2010). Working memory enhances visual perception: Evidence from signal detection analysis. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *36*(2), 441–456. http://doi.org/10.1037/a0018686

Spielberger, C. D., Gorsuch, R. L., Lushene, P. R., Vagg, P. R., & Jacobs, A. G. (1983). *Manual for the State-Trait Anxiety Inventory.* Palo Alto, CA: Consulting Psychologists Press.

Stroud, M. J., Menneer, T., Cave, K. R., & Donnelly, N. (2012). Using the dual-target cost to explore the nature of search target representations. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(1), 113–122. http://doi.org/10.1037/a0025887

Stroud, M. J., Menneer, T., Cave, K. R., Donnelly, N., & Rayner, K. (2011). Search for multiple targets of different colours: misguided eye movements reveal a reduction of colour selectivity. *Applied Cognitive Psychology*, *25*(6), 971–982.

Summers, J. J., Kang, N., & Cauraugh, J. H. (2016). Does transcranial direct current stimulation enhance cognitive and motor functions in the ageing brain? A systematic review and meta- analysis. *Ageing Research Reviews*, *25*, 42–54. http://doi.org/10.1016/j.arr.2015.11.004

Szalma, J. L. (2009). Individual differences: incorporating human variation into human factors/ergonomics research and practice. *Theoretical Issues in Ergonomics Science*, *10*, 377–379. http://doi.org/10.1080/14639220903106361

Szalma, J. L., Schmidt, T. N., Teo, G. W. L., & Hancock, P. A. (2014). Vigilance on the move: video game-based measurement of sustained attention. *Ergonomics*, *57*(9), 1315–1336. http://doi.org/10.1080/00140139.2014.921329

Talsma, L. J., Kroese, H. A., & Slagter, H. A. (2017). Boosting Cognition: Effects of Multiple Session Transcranial Direct Current Stimulation on Working Memory. *Journal of Cognitive Neuroscience*, *29*(4), 755–768. http://doi.org/10.1162/jocn

Teo, F., Hoy, K. E., Daskalakis, Z. J., & Fitzgerald, P. B. (2011). Investigating the Role of Current Strength in tDCS Modulation of Working Memory Performance in Healthy Controls. *Frontiers in Psychiatry*, *2*, 45. http://doi.org/10.3389/fpsyt.2011.00045

Treisman, A. (1977). Focused attention in the perception and retrieval of multidimensional stimuli. *Perception & Psychophysics*, *22*(1), 1–11. Retrieved from http://link.springer.com/article/10.3758/BF03206074

Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *136*, 97–136. http://doi.org/10.1016/0010-0285(80)90005-5

Treisman, A., Sykes, M., & Gelade, G. (1977). Selective attention and stimulus integration. In S. Dornic (Ed.), *Attention and Performance VI*, (pp. 333-361). Hillsdale, NJ:

Lawrence Erlbaum.

Tremblay, S., Lepage, J. F., Latulipe-Loiselle, A., Fregni, F., Pascual-Leone, A., & Théoret, H. (2014). The uncertain outcome of prefrontal tDCS. *Brain Stimulation*, *7*(6), 773–783. http://doi.org/10.1016/j.brs.2014.10.003

Trukenbrod, H. A., & Engbert, R. (2007). Oculomotor control in a sequential search task. *Vision Research*, *47*(18), 2426–2443. http://doi.org/10.1016/j.visres.2007.05.010

Trumbo, M. C., Matzen, L. E., Coffman, B. A., Hunter, M. A., Jones, A. P., Robinson, C. S. H., & Clark, V. P. (2016). Enhanced working memory performance via transcranial direct current stimulation: The possibility of near and far transfer. *Neuropsychologia*, *93*, 85–96. http://doi.org/10.1016/j.neuropsychologia.2016.10.011

Tuddenham, W. J. (1962). Visual Search, Image Organization, and Reader Error in Roentgen Diagnosis. *Radiology*, *78*(5), 694–704. http://doi.org/10.1148/78.5.694

Unsworth, N., & Engle, R. W. (2007). The nature of individual differences in working memory capacity: Active maintenance in primary memory and controlled search from secondary memory. *Psychological Review*, *114*(1), 104–132. http://doi.org/10.1037/0033-295X.114.1.104

Vickers, D., & Leary, J. N. (1983). Criterion Control in Signal Detection. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *25*(3), 283–296.

Vlaskamp, B. N. S., & Hooge, I. T. C. (2006). Crowding degrades saccadic search performance. *Vision Research*, *46*(3), 417–425. http://doi.org/10.1016/j.visres.2005.04.006

von Mühlenen, A., & Conci, M. (2016). The role of unique color changes and singletons in attention capture. *Attention, Perception, & Psychophysics*, *78*(7), 1926-1934.

http://doi.org/10.3758/s13414-016-1139-y

von Mühlenen, A., Muller, H. J., & Muller, D. (2003). Sit-and-Wait Strategies in Dynamic Visual Search. *Psychological Science*, *14*(4), 309–314. http://doi.org/10.1111/1467-9280.14441

von Mühlenen, A., Rempel, M. I., & Enns, J. T. (2005). Unique temporal change is the key to attentional capture. *Psychological Science*, *16*(12), 979–986.

Warm, J. S., Finomore, V. S., Vidulich, M. A., & Funke, M. E. (2015). Vigilance: A Perceptual Challenge. In R. R. Hoffman, P. A. Hancock, M. W. Scerbo, R. Parasuraman, & J. L. Szalma (Eds.), *The Cambridge Handbook of Applied Perception Research* (pp. 241–283). http://doi.org/10.1017/CBO9780511973017.018

Warm, J. S., & Parasuraman, R. (2008). Vigilance Requires Hard Mental Work and Is Stressful. *Human Factors*, *50*(3), 433–441. http://doi.org/10.1518/001872008X312152.

Westerberg, H., & Klingberg, T. (2007). Changes in cortical activity after training of working memory--a single-subject analysis. *Physiology & Behavior*, *92*(1–2), 186–192. http://doi.org/10.1016/j.physbeh.2007.05.041

Wewers, M. E., & Lowe, N. K. (1990). A critical review of visual analogue scales in the measurement of clinical phenomena. Research in Nursing & Health, 13(4), 227–236. http://doi.org/10.1002/nur.4770130405

Wieser, M. J., Pauli, P., Weyers, P., Alpers, G. W., & Mühlberger, A. (2009). Fear of negative evaluation and the hypervigilance-avoidance hypothesis: An eye-tracking study. *Journal of Neural Transmission*, *116*, 717–723. http://doi.org/10.1007/s00702-008-0101-0

Williams, L. (1966). The effect of target specification on objects fixated during visual search. *Perception & Psychophysics*, *1*, 315–318. Retrieved from http://link.springer.com/article/10.3758/BF03215795

Wolfe, J. M. (1994). Guided Search 2.0 A revised model of visual search. *Psychonomic Bulletin & Review*, *1*(2), 202–38. http://doi.org/10.3758/BF03200774

Wolfe, J. M. (2007). Guided search 4.0. In W. Gray (Ed.), *Integrated Models of Cognitive Systems* (pp. 99–119). New York: Oxford.

Wolfe, J. M. (2012). Saved by a log: How do humans perform hybrid visual and memory search? *Psychological Science*, *23*(7), 698–703. http://doi.org/10.1177/0956797612443968

Wolfe, J. M. (2016). Visual Search Revived: The Slopes Are Not That Slippery: A Reply to Kristjansson (2015). *I-Perception*, *7*(3). http://doi.org/10.1177/2041669516643244

Wolfe, J. M., Aizenman, A. M., Boettcher, S. E. P., & Cain, M. S. (2016). Hybrid foraging search: Searching for multiple instances of multiple types of target. *Vision Research*, *119*, 50–59. http://doi.org/10.1016/j.visres.2015.12.006

Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). Guided search: an alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *15*(3), 419–33. http://doi.org/10.1037/0096-1523.15.3.419

Wolfe, J. M., & Horowitz, T. S. (2017). Five factors that guide attention in visual search. *Nature Human Behaviour*, *1*(3), 58. http://doi.org/10.1038/s41562-017-0058

Wolfe, J. M., Horowitz, T. S., & Kenner, N. (2005). Rare items often missed in visual searches. *Nature*, *435*, 439–440. http://doi.org/10.1038/435439a

Wolfe, J. M., Horowitz, T. S., Wert, M. J. Van, Kenner, N. M., Place, S. S., & Kibbi, N. (2007). Low target prevalence is a stubborn source of errors in visual search tasks. *Journal of Experimental Psychology: General*, *136*(4), 623–638. http://doi.org/10.1037/0096-3445.136.4.623.

Wolfe, J. M., & Van Wert, M. J. (2010). Varying target prevalence reveals two dissociable decision criteria in visual search. *Current Biology*, *20*(2), 121–4. http://doi.org/10.1016/j.cub.2009.11.066

Woodman, G. F., & Arita, J. T. (2011). Direct Electrophysiological Measurement of Attentional Templates in Visual Working Memory. *Psychological Science*, *22*(2), 212-215. http://doi.org/10.1177/0956797610395395

Woodman, G. F., & Luck, S. J. (2004). Visual search is slowed when visuospatial working memory is occupied. *Psychonomic Bulletin & Review*, *11*(2), 269–274. http://doi.org/10.3758/BF03196569

Woods, D. L., Kishiyamaa, M. M., Lund, E. W., Herron, T. J., Edwards, B., Poliva, O., Hink, R. F., & Reed, B. (2011). Improving digit span assessment of short-term verbal memory. *Journal of Clinical and Experimental Neuropsychology*, *33*(1), 101–111. http://doi.org/10.1080/13803395.2010.493149

Yuen, T. G. H., Agnew, W. F., & Bullara, L. A. (1981). Histological evaluation of neural damage from electrical stimulation: considerations for the selection of parameters for clinical application. *Neurosurgery, 9*(3), 292-299. https://doi.org/10.1097/00006123-198109000-00013

Zelinsky, G. J. (2008). A theory of eye movements during target acquisition. *Psychological Review*, *115*(4), 787–835. http://doi.org/10.1037/a0013118

Zelinsky, G. J. (2012). TAM: Explaining off-object fixations and central fixation tendencies as effects of population averaging during search. *Visual Cognition*, *20*(4–5), 515–545. http://doi.org/10.1080/13506285.2012.666577

Zoest, W. Van, Donk, M., & Theeuwes, J. (2004). The Role of Stimulus-Driven and Goal-Driven Control in Saccadic Visual Selection. *Journal of Experimental Psychology: Human Perception and Performance, 30*(4), 746-759. http://doi.org/10.1037/0096-1523.30.4.749

Zwissler, B., Sperber, C., Aigeldinger, S., Schindler, S., Kissler, J., & Plewnia, C. (2014). Shaping memory accuracy by left prefrontal transcranial direct current stimulation. *The Journal of Neuroscience*, *34*(11), 4022–4026. http://doi.org/10.1523/JNEUROSCI.5407-13.2014